Mass Evacuation of Persons Needing Mobility Assistance: A Holistic Approach for Dedicated Route Selection and Traffic Microsimulation Modeling

by

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Dedicated to

I dedicate this thesis to my loving parents and supportive siblings whose unwavering encouragement and endless support have been instrumental in my academic journey.

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Abstract

This thesis presents a comprehensive approach to emergency evacuation planning for persons needing mobility assistance (PMA). The study contributes by combining multi-criteria decision analysis and microsimulation-based modeling. The initial phase of this study focuses on determining optimal evacuation routes using the entropy weight method, cloud model optimization, and TOPSIS method. Through a hybrid approach, the study evaluates six alternative evacuation routes within the Halifax peninsula and identifies Route 2 as the optimal choice for PMA evacuation. Next, the study develops a microsimulation model for traffic evacuation, incorporating designated routes for PMA evacuation. The model considers different network conditions and evaluates Average Evacuation Time (AET) for emergency vehicles (EMVs) exiting the peninsula. The results highlight the fastest routes for both "Out of Danger Zone" (ODZ) and "To the Shelter Location" (TSL) scenarios, taking into account traffic volume variations and dedicated lanes. The findings provide insights into efficient evacuation strategies, validating the proposed methodology's effectiveness in selecting evacuation routes for PMA. The outcome of this research contributes to proactive evacuation planning and enhances policymakers' ability to address the specific needs of PMA during natural disasters.

List of Abbreviations and Symbols Used

PWDs	Persons with Disabilities
PMA	Persons Needing Mobility Assistance
MCA	Multicriteria analysis
MCDA	Multi-Criteria Decision Analysis
EWM	Entropy Weight Method
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TV	Traffic Volume
TC	Traffic Capacity
C	Congestion
TS	Travel Speed
TD	Total Distance
LW	Lane Width
RC	Road Condition
IP	Incident Probability
AAWT	Annual Average Weekday Traffic
MTV	Maximum Traffic Volume
BCG	Backward Cloud Generator
PIS	Positive Ideal Solution
NIS	Negative Ideal Solution
EMVs	Emergency Vehicles
AET	Average Evacuation Time
ODZ	Out of Danger Zone
TSL	To the Shelter Location
DTA	Dynamic Traffic Assignment

Glossary

Multicriteria Decision Analysis	A decision-making approach that considers multiple criteria or factors when evaluating alternatives. It involves assessing the trade-offs between different criteria to identify the most suitable option.
Entropy Weight Method	A mathematical approach used in decision-making and evaluation processes. It calculates the weights of criteria based on their relative importance and helps in prioritizing alternatives.
TOPSIS Application	TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a decision-making method that compares alternatives based on their proximity to an ideal solution and farthest from a negative solution.
Transport Network	A system comprising interconnected links and nodes that enables the movement of traffic.
VISSIM	A widely used traffic microsimulation software that allows for the realistic modeling and analysis of transportation systems.
Traffic Microsimulation	Simulating traffic flows at a detailed level to study and analyze the behavior and interactions of individual vehicles.
Traffic Assignment	The process of assigning traffic flow to different routes or paths between specific origins and destinations in a transport network.
Origin	The starting point of a trip or journey.
Destination	The endpoint or final location of a trip or journey.
Dynamic Traffic Assignment	A modeling technique that captures the dynamic spread of congestion over space and time within a transport network.
Queue Length	The number of vehicles waiting in a line or queue on a link in the transport network, often caused by congestion or traffic signals.
TOPSIS Application	TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a decision-making method that compares alternatives based on their proximity to an ideal solution and farthest from a negative solution.
Transport Network	A system comprising interconnected links and nodes that enables the movement of traffic.

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Chapter 1

Introduction

1.1 Background and Motivation

The process of collectively transporting people out of a dangerous zone via a variety of transportation alternatives and evacuation routes in the case of a natural or man-made disaster is called an evacuation process. Throughout the last several decades, there has been an unusually high number of hurricanes and other catastrophes that have forced individuals to evacuate their homes. Hurricane Katrina caused enormous destruction in the history of the United States. Hurricane Katrina caused significant fatalities and extensive property damage. It was among the top three of the five costliest and deadliest storms to strike the United States *(Knabb, et al., 2006)*. Many people were killed and injured when Katrina, a Category 1 hurricane on the Saffir-Simpson scale, struck southern Florida. According to estimates, Hurricane Patricia (2015), with its peak wind speed of 165 mph, is the most powerful major Pacific storm ever recorded. The flooding that happens near the coast as a result of storms is equally dangerous to people and their property as the storm's forces *(Swamy et al., 2017)*. According to estimates provided by various researchers, Hurricane Katrina (2005) was responsible for $125 billion worth of property damage, while Hurricane Sandy (2012) was responsible for $71.4 billion *(Blake et al., 2013)*. Building the infrastructure to evacuate an entire city's residents in a matter of hours is not socially, environmentally, nor economically possible. The inability of the transportation network to satisfy the extra demand that would follow from an evacuation further complicates the problem. The fact that 100,000 to 300,000 persons during Hurricane Katrina, notably disabled city residents and low-income city residents, were not or could not be evacuated cast a shadow over the success of the highway-based evacuation plan *(Wolshon, 2006)*. The United States suffered its seventh costliest hurricane with Rita, whereby southeast Texas gulf coast and southwest Louisiana all suffered losses due to Hurricane Rita. A major disaster area in Texas covered over 25,000 square miles, and $10 billion in damages were estimated to be caused by the hurricane *(Mayer and Dale, 2008)*. The people of coastal communities were instructed to evacuate, and those without cars were provided with free bus transportation. There was an increase in the number of individuals who abandoned their homes in response to official orders. This resulted in a huge increase in automobile-related traffic difficulties *(Blumenthal, 2005)*. As three million Texans evacuated the coast, 100 miles of congestion left many stranded and without gas. The fifty-mile journey from Galveston Island and other low-lying areas to Houston took four to five hours, as flooded roadways slowed traffic to a few miles per hour (Litman, 2006). Hurricane Florence's severe rainfall and flooding is estimated to have cost between $16 billion and $40 billion, claiming the lives of 53 people in North Carolina (NC), South Carolina (SC), and Virginia (VA) *(Paul and Sharif, 2019)*. The aforementioned natural catastrophes compelled millions of people to abandon their homes and towns, resulting in mass evacuation on city and regional levels. During Hurricana Katrina more than 1.2 million people evacuated the New Orleans metropolitan region, leaving around 100,000 residents in the city itself. The Superdome housed over ten thousand people who were still alive at the time of the hurricane. Moreover, almost 3 million people along the Texas Gulf Coast were forced to evacuate in September 2005 as Hurricane Rita approached, and up to 1.7 million people in South Carolina, North Carolina, and Virginia followed mandatory evacuation orders during Hurricane Florence.

Canada faces an elevated risk of experiencing more natural disasters due to climate change and the increasing frequency of wildfires. 88,000 people were evacuated from their homes in Canada's largest wildfire evacuation on May 3, 2016. Around 2,400 buildings were lost in the Fort McMurray wildfire, making it Canada's biggest natural catastrophe, as the fire caused $6 billion in commercial and personal damages *(Mamuji and Rozdilsky, 2019)*. In June 2013, significant flooding and widespread evacuations occurred in southern Alberta as a result of rapid snowmelt in the Canadian Rocky Mountains and heavy rainfall, hence approximately 120,000 people were evacuated *(Fulton and Drolet, 2018)*. Due to the historical frequency with which natural disasters have happened in Nova Scotia, the province is susceptible to such occurrences. In 2023, Nova Scotia experienced severe wildfires, resulting in the evacuation of approximately 16,000 people, including residents of senior care institutions with disabled individuals located in the affected areas. The fires severely damaged approximately 200 buildings and structures in the affected areas *(Bilefsky and Campbell, 2023)*. In 2022 Hurricane Fiona made landfall in Nova Scotia, causing major tree and electrical line damage throughout the province. Huge trees fell, causing damage to buildings and automobiles, and leaving over 415,000 people in Nova Scotia without electricity *(Pasch, et al., 2023)*. Hurricane Dorian extensively damaged the Halifax harbor and tore off the roof of an apartment building in the south end. A construction crane toppled, resulting in around 400,000 Nova Scotia Power customers losing power *(Groff, 2020)*. Hurricane Juan in 2003 will be remembered as the most devastating hurricane in Halifax's modern history due to the massive tree loss, power outages, and destruction of homes. In Nova Scotia and Prince Edward Island, between 800,000 and 900,000 people were left without electricity as a result of the hurricane's catastrophic path through the province *(Fogarty, 2003)*. The recent tragic wildfires and above-mentioned disasters emphasize the crucial significance of planning for the evacuation of vulnerable populations and serve as a reminder that disasters can occur in and around the Halifax Peninsula. Inadequate preparation, vehicle collisions, and events like those that occurred during Hurricanes Katrina, Rita, and Florence can all lead to a deterioration of the situation during evacuations. It is important to understand the complexities of the evacuation process in order to be better prepared and responsive in the event of an emergency.

Mass evacuations pose unique challenges for vulnerable populations, particularly in terms of transportation planning and related traffic and transportation issues. One of the primary challenges is ensuring the accessibility and availability of transportation options that cater to the specific needs of vulnerable individuals, such as persons with disabilities (mental and physical), older adults, and those needing mobility assistance. Limited accessible transportation resources and inadequate emergency evacuation route planning between transportation providers and emergency management agencies often result in difficulties for vulnerable populations to access safe evacuation routes. Moreover, the sheer volume of evacuees and the urgency of the situation can lead to congestion and traffic bottlenecks, further exacerbating transportation challenges. Traffic management during mass evacuations becomes complex, and delays in providing appropriate transportation options for vulnerable populations can put their safety and well-being at risk. Therefore, it is of utmost importance to incorporate the needs of vulnerable populations into route planning with predetermined designated evacuation routes. Consideration should be given to factors such as accessibility, proximity to medical facilities, and the availability of vehicles equipped to accommodate special requirements. To effectively address these challenges, a holistic approach for dedicated route selection considering multiple criteria and traffic evacuation modeling is needed, specifically for the mass evacuation of persons requiring mobility assistance. This approach entails comprehensive transportation planning that takes into account the specific needs of vulnerable populations. In addition, coordination among transportation agencies and emergency management entities is crucial to ensure the safe and timely evacuation of these individuals. Ultimately, route planning with a focus on the needs of the vulnerable population contributes to a more inclusive and resilient emergency management system, capable of effectively addressing the unique challenges faced by those who require additional assistance during evacuations.

The procedure of evacuating a location is itself a complicated procedure. Despite the fact that a mass evacuation is an occurrence with an uncertain outcome, route planning via route selection models and traffic evacuation simulation models can be utilized to analyze and comprehend an evacuation operation. The information obtained from these models can be utilized for emergency planning and decision-making. Nonetheless, there are many potential hazards to networks that make evacuation route planning and modeling difficult. Issues in mass evacuation planning include network architecture, vulnerable people, and lack of resources. For instance, Canada's Halifax Peninsula has only five exit/entry points, which poses a threat to the entire network. This region is likely to flood because it is in the hurricane's course. The historic city's narrow roadways make it difficult to navigate the neighborhoods during rush hour. Consequently, those on the peninsula who are vulnerable due to their geophysical, social, or mobility requirements may require prioritized evacuations. The mortality risk of the disabled population during a natural disaster is higher that of the general population. Evacuation plans must be in place prior to, during, and after any form of disaster. Compared to other Canadian provinces, Nova Scotia has the greatest percentage of residents with disabilities. 32.4 percent of females and 28.1 percent of males are reported to have at least one handicap, with 13.3 percent having mobility-related disabilities and 6.6 percent having vision-related difficulties *(Government of Nova Scotia, 2017)*. Due to this fact, Governments and other relevant entities in this space have a special responsibility to ensure that individuals with disabilities can be evacuated and relocated to emergency shelters securely. It is crucial to include the disabled population in evacuation plans when creating a comprehensive evacuation strategy for a city. Evacuation plans must take into account the fact that the needs of the disabled population vary from those of the able-bodied population. The field of disaster evacuation research has witnessed growth in recent years, evident through the emergence of studies focusing on evacuation behavior analysis and traffic evacuation operations. Within the academic literature, a diverse range of studies exists concerning the transportation of patients or individuals with disabilities. Several illustrations of such studies are outlined below.

Zhao et al. (2017) developed a modified an optimization strategy that is combined with a mathematical model to minimize total weighted evacuation time in relation to the total shelter area and population. Total shelter area, evacuation time, and population are all investigated as factors. Total weighted evacuation time is positively correlated with population size and negatively correlated with total shelter area, with population size exerting a much greater influence on total weighted evacuation time than total shelter area. To reduce the total time spent evacuating, *Bayram and Yaman (2015)* constructed a nonlinear mixed-integer programming that determines where shelters should be located and how people should be distributed between them. Using second-order cone programming techniques, they presented a method for solving problems of realistic proportions. Using their model, the equilibrium between efficiency and fairness (ensuring equitable treatment for all evacuees), as well as the significance of shelter site quantity and locations can be examined. Their results show that the percentage of people evacuated by a certain time increases, while the total evacuation time and maximum latency decrease when more shelters are set up and evacuees are persuaded to accept a larger degree of tolerance. In order to facilitate emergency logistics tasks during the response phase of a disaster, *Sheu and Pan (2014)* outline a strategy for building a centralized emergency supply network. The proposed procedure employs a three-phased approach to programming. The programming model begins with the shelter network design, then moves on to the medical network design, and finally to the distribution network design. Multi-objective functions and mixed-integer programming are used at every stage of the programming model to minimize travel time, actual expenditure on operations, and psychological strain. While the aforementioned studies do include the shelter site network and analyze the impacts of total shelter area and shelter locations on overall evacuation time, they lack consideration for the needs of people with disabilities. For instance, people with disabilities (PWDs) are more prone than able-bodied people to experience health issues during an evacuation, hence PWD-specific shelters with emergency support and professionals prepared to deal with any injuries and complications sustained by PWDs may be necessary.

Previous evacuation planning studies have predominantly focused on incorporating public transportation and private vehicles in the planning process, neglecting the specific needs and requirements of individuals who rely on special needs vehicles, such as individuals requiring mobility assistance and those with acute health conditions. *Swamy et al. (2017)* developed a framework for making efficient use of existing public transportation resources, in this instance buses, to transport individuals from high-risk areas to safe-zone shelters. They propose multi-step approach, whereby the first step is the planning framework, which locates pickup points, allocates them to shelters, and creates a preliminary network of routes. In the second step, they ensure that routes with higher demand receive more trips and that trips to a route are spread evenly. *Abdelgawad and Wahba (2010)* introduce a new approach for evacuation optimization that takes into account both private vehicles and public transportation systems. In their study, in the case of mass transit evacuation, the multi-objective method optimizes the multimodal evacuation framework by weighing three objectives: reducing journey time in vehicles, reducing delay time at the point of origin, and reducing fleet costs. Their results suggest a 12% drop in the required size of the mass transit fleet and a 13% increase in the network clearance time for evacuees using public transportation. *Pereira and Bish (2015)* presented a variant of the vehicle routing problem for regional evacuation planning with buses, assuming that evacuees arrive at designated pickup locations at uniform rates. The issue seeks to reduce wait times while taking advantage of cost-saving opportunities afforded by service customization. Their study chose two crucial strategic criteria, the maximum number of pickups allowed at each site and the fleet size. The studies mentioned above predominantly focus on evacuation optimization strategies related to public transportation and private automobiles, either individually or in conjunction. The studies identified all designated pickup locations where individuals must congregate in order to be evacuated. However, the issue remains that able-bodied people and PWDs who are mobile and do not require assistance can congregate at pick-up locations. Conversely, Immobile PWDs defined as Persons Needing Mobility Assistance (PMA) in this study, require assistance to navigate and are unable to congregate at pick-up locations. A further concern is that public transportation vehicles may not be suitable for PMA evacuation, necessitating the use of emergency vehicles.

In evacuation planning, large-scale traffic microsimulation models are often used by many researchers. *Edara and McGhee (2010)* developed large-scale evacuation network traffic models. Their investigation models 10 cities' 2,000-mile road networks (motorways, arterials, and surface streets). The investigation succeeds in estimating evacuation routes performance, network-wide evacuation time, critical bottlenecks, congestion, and other operational difficulties. Also, traffic control plan modifications are suggested to improve traffic evacuation performance. The simulation results of their model showed that the entire evacuation time was significantly affected by factors including traffic demand, traffic capacity, and reversed lanes. *Kwon and Pitt (2005)* examined how Dynasmart-P, a dynamic traffic assignment model, could be utilized to compare the efficacy of various evacuation plans for downtown Minneapolis, Minnesota. Their research demonstrates the viability of employing the Dynasmart-P model to develop and evaluate evacuation strategies in the context of a large metropolitan network. *Theodoulou and Wolshon (2004)* conducted a study of an evacuation, wherein the flow of traffic on stretches of roadway with contraflow was studied in order to gain a greater understanding of traffic conditions. Using the CORSIM microscopic traffic simulation program, models of the road layout that would be used to evacuate New Orleans and two alternative scenarios for this segment were created. Their findings indicated that the proposed configuration could lead to insufficient use of the contraflow stretch, making it much harder for people to leave the city. Also, their analysis revealed that the efficacy of the New Orleans contraflow segment could be significantly improved by implementing a few simple, low-cost modifications to the current configuration. Despite the fact that previous researchers have utilized a variety of simulation models to plan for large-scale traffic evacuations, the problem persists: the routes selected for evacuation planning are not designated evacuation routes that take into account numerous criteria related to road and traffic conditions, that influence the effectiveness with which PMA evacuate. For example, routes used in PMA evacuation plans must meet certain criteria, such as having wider lanes, a low incidence probability, and good conditions to transport people securely. Wider lanes allow for a more efficient evacuation because wider emergency vehicles may be required for PMA evacuation. PMA are more likely to expire if an emergency vehicle is involved in a traffic collision during an evacuation operation; therefore, evacuation routes with a low probability of incidents will improve the safety of PMA. Lastly, routes with poor road conditions are more prone to traffic congestion and collisions, so routes with good road conditions are preferred for PMA evacuation planning.

Many researchers improved evacuation planning by developing strategies for evacuation route planning. *Chiu and Mirchandani (2008)* developed a hypothetical scenario using a simulation-based traffic flow optimization strategy, in which evacuees were offered a choice between multiple system-optimal evacuation routes and made their own individual judgments regarding which route to take based on their own unique route-choice behavior. Their principal discussion is the practicability of measuring routing efficacy in the context of route-choice behavior. This research introduces a behavior-robust feedback information routing (FIR) method to enhance system performance. Their results show that evacuation effectiveness is drastically diminished when people choose non-optimal evacuation routes, and providing constantly updated information via FIR on evacuation routes is an efficient strategy. A route planning method has been developed by *Campos and Bandeira (2012)* for determining the best possible evacuation routes in the event of an emergency. Their method employs an iterative heuristic algorithm to allocate vehicle flows to shelters during evacuation planning, taking into account travel time and transportation network capacity. Their technique can be used for establishing the optimal evacuation routes away from an impending disaster area and to establish shelter locations. *Yuan and Wang (2007)* developed a multi-objective path selection model for use in evacuation scenarios. In their model, both total traveling time and path complexity are optimized. A continuous decaying function of travel speed along each arc represents the effect of the disaster's extension in real-time. The totality of a path's arcs is representative of its complexity. The aforementioned research took into account factors including travel time, network capacity, travel speed, and route complexity when developing techniques for selecting evacuation routes in the event of a disaster. Hence, there exists a significant gap in the comprehensive analysis of criteria for selecting the most optimal evacuation routes. Evacuation route selection models should perform a comprehensive analysis of criteria, including traffic volume, capacity, congestion, and total distance. In addition, the comprehensive evacuation route selection model for PMA evacuation should take into consideration vehicle incident probability, road condition, and lane width for the safe evacuation of PMA by emergency vehicles.

A few researchers have focused on evacuation planning considering the needs of the disabled population, but scarcity still exists in evacuation planning studies for PMA. *Baou et al. (2018)* did research into evacuation scenarios that led to the development of an interesting mathematical linear programming model that accounts for various types of evacuees, such as those who are able to walk, those who require wheelchairs, and those who require ambulance transport. The goal of their study was to reduce the total time required to evacuate everyone from a given set of locations, taking into account any applicable restrictions, and the results indicated that evacuation time has a strong correlation with service time for evacuees with disabilities. In addition, evacuation time reaches a tipping point as more vehicles of all categories are involved, after which additional vehicles have little impact, especially for the evacuation of disabled individuals. *Lehuédé et al. (2014)* developed a model to examine the evacuation for those with mental disorders. Although these individuals do not require assistance entering or exiting vehicles, they cannot use public or private transportation because they lack independence. Their study employs a large neighborhood search approach to address this issue. They looked into the feasibility of using mini vehicles with eight seats to carry adults to vocational rehabilitation facilities, children with impairments to specialized schools, and children with disabilities to traditional schools. In a subsequent study, *Feillet et al. (2014)* studied transporting individuals with special needs and developed the formulation of a new time-consistent vehicle routing problem. The researchers analyzed the temporal consistency of the routing problem at various time intervals. They concluded that maintaining a regular schedule can substantially reduce transportation costs. The preceding research handled PWDs' evacuation by optimizing vehicle allocation and utilizing specialized vehicles based on evacuation destinations. However, there is a lack of pre-planned evacuation routes that account for traffic, road conditions, and time constraints affecting the safe evacuation of PMA. For the safe evacuation of PMA, pre-planned evacuation routes are essential. PMA are more likely to expire during an evacuation than individuals without disabilities. This corresponds to the selection of designated evacuation routes that can be utilized in the event of an emergency.

Creating a comprehensive evacuation plan that takes into account the specific needs of PMA is essential in light of the aforementioned research gaps. Due to the scarcity of evacuation planning for PMA, there is a critical requirement, knowledge, and practical application gap when it comes to mass evacuations of PMA on a city or regional scale. This gap can be closed by selecting appropriate dedicated emergency evacuation routes in consideration of dynamic traffic and road conditions. In order to identify the safest possible means of evacuation for PMA, the purpose of this study is to develop a model for selecting routes that take into consideration traffic and road condition-related criteria. As a result of the route selection model, this study designates four ideal evacuation routes of Halifax Peninsula, Nova Scotia for PMA evacuation. Next, this study integrates these routes into the traffic evacuation microsimulation model to establish the Average Evacuation Time (AET) for a single emergency vehicle to evacuate the peninsula. The traffic evacuation microsimulation model exclusively employs emergency vehicles to evacuate PMA from Halifax Peninsula hospitals and senior care facilities using designated evacuation routes.

1.2 Technical Objectives

The overall goal of this study is to develop a comprehensive evacuation framework for the vulnerable population, defined as PWDs and PMA in this study. In order to achieve its goal, the research would accomplish the following specific objectives.

1. To explore dedicated evacuation routes that facilitate the mass evacuation of PMA by considering multiple criteria related to traffic and road conditions.

2. To Develop a Route Selection Model through Multi Criteria Analysis (MCA), which considers multiple traffic and road condition related criteria.

3. To develop a comprehensive microsimulation modeling framework for the evacuation of PMA in dual destination scenarios: Out of Danger Zone (ODZ) and To the Shelter Location (TSL).

4. To test and evaluate the performance of designated evacuation routes for dual-destination scenarios under three distinct traffic volume/condition related cases.

Objectives 1 and 2 are addressed in Chapter 2. Objectives 3 and 4 are addressed in Chapter 3.

1.3 Significance

This thesis makes a significant contribution to the field of emergency evacuation planning, particularly in addressing the specific needs of PMA during evacuations. By proposing a comprehensive methodology and framework, the thesis offers valuable insights and practical solutions for policymakers and emergency personnel. The significance of this thesis lies in its practical applicability for policymakers and emergency professionals. The proposed methodologies and frameworks enable the development of proactive evacuation strategies, considering the unique needs of PMA. By optimizing selection of dedicated evacuation routes and accurately simulating evacuation traffic flow, the thesis contributes to the improvement of overall evacuation efficiency, reducing evacuation time, and ensuring the safety of PMA during emergency evacuation operations.

Overall, this thesis expands the knowledge and understanding of emergency evacuation planning, emphasizing the importance of evacuation route planning, such as selection of designated evacuation routes, while focusing on engineering related criteria and goals. The lessons learned from this study provides a valuable resource for researchers, practitioners, and policymakers involved in emergency management, offering effective approaches and tools for addressing the challenges of evacuating persons needing mobility assistance during emergencies.

1.4 Thesis Outline

This thesis comprises four chapters. The various parts of the thesis are separated into individual Chapters, as seen in the following figure 1-1.

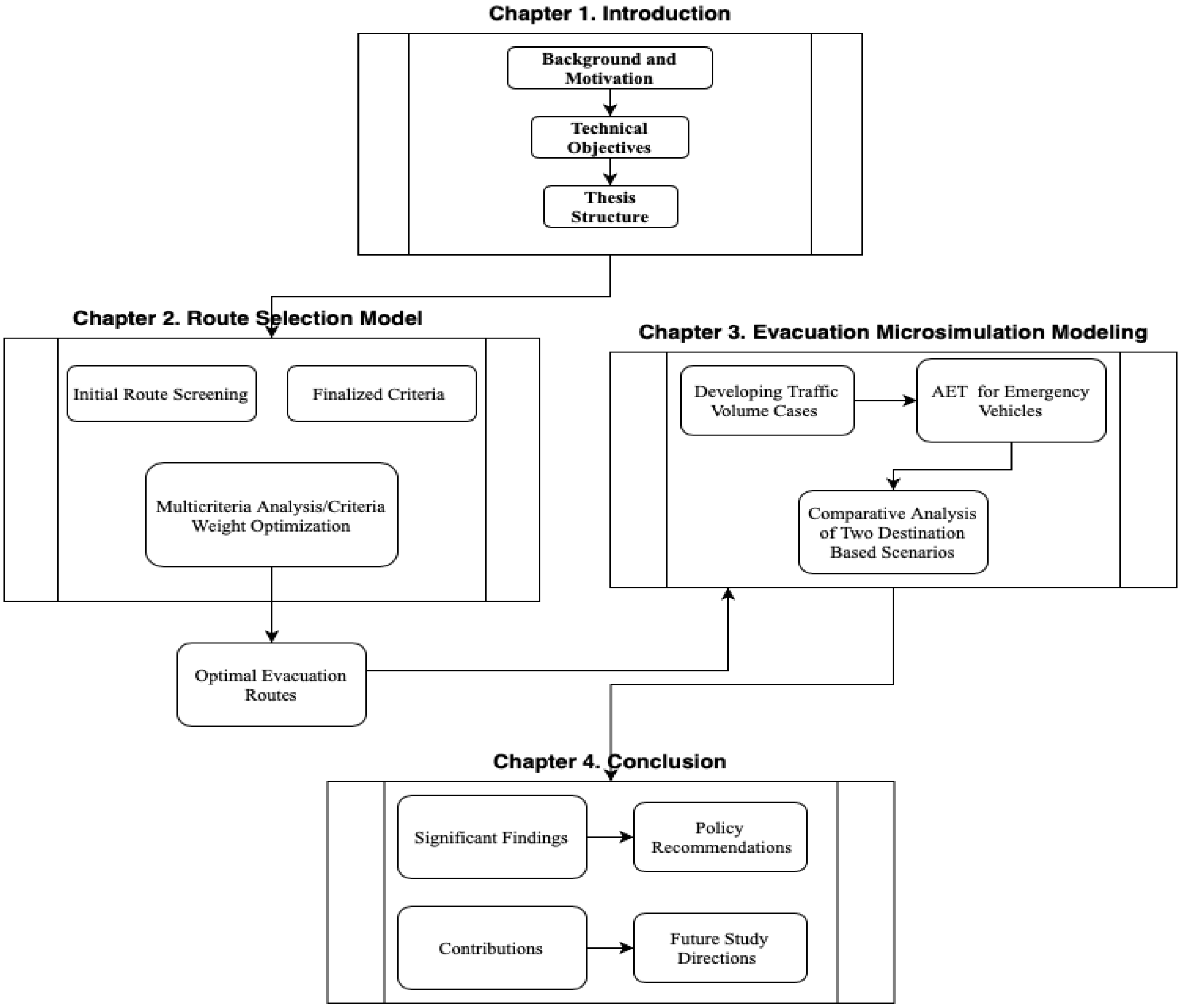

Figure 1-1: Thesis Structure and Key Chapter Components

Chapter Two discussed the conceptual framework of the route selection model. The chapter establishes initial route selection criteria, performs analysis to decide on finalized traffic and road condition related criteria, gives initial criteria weights, and combines objective/subjective weights to get optimized criteria weights. Finally, it ranks evacuation routes from best to worst.

Chapter three focuses on evacuation microsimulation modeling considering optimal evacuation routes obtained by the route selection model. This chapter develops three distinct traffic volume cases under two destination based scenarios, within the traffic evacuation microsimulation model. Also, this chapter performs a comparative analysis between two destination based scenarios.

Chapter four concludes with a review of the most significant findings and recommendations for policy directions from the study, as well as an outline of the authors' contributions and directions for future study.

Chapter 2

Route Selection Model[1] [2] [3]

2.1 Introduction

Disasters caused by nature including hurricanes, tornadoes, earthquakes, flooding, wildfires, and cyclones are prevalent around the world. According to statistics *(The Statistics Portal, 2022)* of the year 2015, most natural catastrophes happened in the following countries, the United States (43 occurrences), Indonesia (28 occurrences), and India (19 occurrences). Natural disasters can result in extensive property destruction, monetary losses, and loss of human life. Hurricane Katrina became one of the most destructive natural catastrophes in the U.S. history, killing thousands of people and knocking out power to millions more *(Knabb et al., 2006)*. When a natural disaster threatens the safety of a region, government agencies frequently issue forced evacuation orders for the most vulnerable locations. One potential method to evacuate is by using the individual's personal vehicle. The population's social and demographic attributes (e.g., age, gender, race, and health difficulties) can have a substantial impact on their driving ability, both in regular and hazardous driving situations (e.g., emergency evacuation) *(Dulebenets et al., 2019)*. Hurricane Katrina, which struck New Orleans in 2005 and caused severe flooding when the city's levees failed, brought to the forefront the need for

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[1] This chapter is adapted from:

Memon, A.W., and Habib, M. A. (2023). Enhancing Evacuation Planning for Individuals Requiring Mobility Assistance: A Multi-Criteria Decision Analysis Approach to Route Selection. *Natural Hazards. (Under Review)*

[2] Memon, A. W., and Habib, M. A. (2023). "Multi Criteria Decision Analysis Approach to Route Selection for Evacuation Planning of Persons Needing Mobility Assistance", Peer-reviewed proceedings of 102nd Annual Meeting of the Transportation Research Board, Washington DC, January 8-12, 2023 (No. 23-03232).

[3] Memon, A. W., Habib, M. A. (2022). An Efficient Approach to Route Choice for Evacuation Planning of Persons with Disabilities. The Association of Collegiate Schools of Planning (ACSP), November 02-05, 2022

evacuation strategies for those without cars, vulnerable populations, and those in precarious situations. Over 60-year-olds accounted for the great majority of fatalities *(Renne, 2018)*. Although planning and regulation of evacuation planning for vulnerable persons are still a work in progress, *Renne (2018)* points out that there are several strong reasons why society cannot afford to disregard evacuation preparation for these individuals. Today, rising sea levels, climate change, and the threat of flooding are the first and most pressing concerns *(Renne, 2018)*. According to studies, sea levels might rise between 0.8 and 1.05 meters by 2100, with the majority of scientists predicting a 1-meter rise *(BAMBER and ASPINALL, 2013; Rignot et al., 2011)*. Due to climate change, the threat of natural disasters is greater now than in past. It is predicted that climate change will cause inundation, including storm induced coastal flooding, frequent wildfires and more severe weather disasters *(Renne, 2018)*. According to academics, extreme weather caused by climate change necessitates better emergency transportation and evacuation planning, including the usage of public transit during extreme weather *(Koetse and Rietveld, 2012; Potential impacts of climate change on U.S. transportation, 2008)*. Due to shift demographics and society's aging population, evacuation planning must include planning specifically for the carless and vulnerable. As the population ages, an increasing number of people will be unable to drive or may require specific medical equipment for travelling, therefore, ignoring this information could result in major complications during an emergency evacuation *(Renne, 2018)*.

To date, most studies have considered evacuation research for the general population, few previous studies have considered Persons with Disabilities (PWDs), and emergency evacuation planning for Persons Needing Mobility Assistance (PMA) who require mobility assistance has not gotten nearly as much attention as evacuation preparation for the general population. This study differentiates PWDs and PMA in the following manner, PWDs are able to self-evacuate if emergency evacuation management provides them with the necessary instructions. In contrast, the PMA population consists of those who are unable to leave their residences without human or other life-saving assistance. For example, *Egodage et al. (2020)* examined fire emergency evacuation strategies for PWD's in high-rise structures. The study, however, was missing the consideration for evacuation of PMA, which makes it challenging to plan and perform an efficient evacuation *(Egodage et al.,* *2020)*. In a separate research area, a spatial model of building interiors was created to better meet the special evacuation planning and routing needs of those with disabilities *(Hashemi and Karimi, 2016)*. The accessibility index of a spatial model addresses PWDs and does not consider PMA. In other cases, researchers have pinpointed a variety of challenges unique to the evacuation of healthcare facilities and senior care centres. *Hashemi (2018)* summarized the important findings in the literature on emergency evacuation of PWDs, as well as the relevant flaws and research gaps that need to be addressed in the future. Due to the lack of evacuation planning for PMA, there is an urgent need, knowledge and practical application gap when it comes to mass evacuations of PMA on a city or regional scale. Closing this gap includes selecting optimal emergency evacuation routes considering traffic and road condition related criteria. Thus, this research aims to develop a route selection model considering traffic and road condition related criteria to find the best possible emergency evacuation routes for PMA. The technical objectives of this study are: (1) Establishing initial route selection criteria; (2) deciding traffic and road condition related criteria affecting the emergency evacuation process; and (3) selection of optimal emergency evacuation routes for PMA through a multicriteria analysis (MCA). In pursuit of this objective, the study establishes a comprehensive framework dedicated to identifying optimal emergency evacuation routes, specifically targeting the evacuation of PMA. The route selection model is constructed through a thorough examination of alternative evacuation routes within the Halifax peninsula. This is accomplished by employing a hybrid approach that combines Entropy Weight-Cloud Optimization-TOPSIS methodologies. Within the proposed MCA framework, this study takes into account eight criteria related to traffic and road conditions that significantly impact the emergency evacuation process. These criteria are carefully considered across six distinct routes, allowing for a comprehensive analysis of their influence on the overall evacuation effectiveness. Factors including Traffic Volume, Traffic Capacity, Congestion, Travel Speed, Lane Width, Road Condition, Incident Probability, and Total Distance are taken into account. The Halifax Regional Municipality's (HRM) open data portals *(HRM, 2022)* provided the data that were used to develop these criteria. The findings present a ranking of the evacuation routes from the most favorable to the least favorable, providing empirical evidence that supports the scientific validity and accuracy of the proposed method for conducting MCA in the selection of emergency evacuation routes for PMA. For the purpose of evacuation, the focus will be on considering the top three routes that have been ranked as the most favorable.

2.2 Literature Review

In recent decades, there has been a rising corpus of academic literature advocating for a greater need for thorough and holistic evacuation planning and modeling *(Knabb et al., 2006)*. Since Hurricane Katrina in 2005, major issues such as facilitation of evacuation planning route selection in evacuation plans for PWDs and PMA have been frequently acknowledged as a problem by disaster management professionals. Adaptive modelling, simulation, and advanced optimization methods are being used in some emergency evacuation planning research to assist PWDs. *Manley et al. (2012)* introduced an agent-based model that can be utilized by all private enterprises for creating and testing a collaborative decision support system, as well as for designing an urgent evacuation strategy to sustain business continuity. The approach presented by the above-said model is developed for the specific purpose of evacuating PWDs in the event of an emergency *(Manley et al., 2012)*. The Exitus system, created by *Manley et al. (2012)*, is superior to prior evacuation models because it takes into account a broader range of mental and physical characteristics exhibited by a challenged individual, and generates more accurate simulations of varied populations. In another study, *Kaisar et al. (2012)* developed a public transportation routing scenario that best supports special needs groups in the District of Columbia's downtown core using a linear programming optimization approach. The main goal of the above-mentioned study was to propose optimum locations for evacuation bus stops, and the construction of a realistic microscopic transportation network simulation model *(Kaisar et al., 2012)*. *Kaisar et al. (2012)* concluded that the scenario with 60 evacuation bus stop locations would be optimum for planning considerations. With the finest spatial spread of evacuation bus stations, this scenario had the lowest delay, travel, and stop times. Another research optimization model for the evacuation of PWDs was introduced by *Ebrahimnejad et al. (2021)*. This study developed a linear mixed integer programming model. The goal of this study was to find the best way to allocate different types of PWDs to different types of vehicles, and to route cars to pick up PWDs during evacuations *(Ebrahimnejad et al., 2021)*. Driving simulators were employed in a few studies of evacuation planning considering PWDs. For example, *Abioye et al. (2020)* deployed a Vehicle operation simulator to replicate real-world emergency evacuation scenarios and examine individuals' reported driving problems during an evacuation. The Vehicle operation simulator was utilized to inform Predictive models of the cognitive demands imposed on evacuees. According to a statistical study conducted by *Abioye et al. (2020)*, more experienced drivers reported higher degrees of mental, physical, temporal, effort, and frustration than less experienced drivers. Furthermore, in the event of a natural catastrophe, the population of a certain metropolitan area will have to evacuate, and *Dulebenets et al. (2020)* have developed a novel multi-objective optimization model to reduce the evacuation duration, physical energy, and stress involved in doing so. In addition, *Dulebenets et al. (2020)* constructed an optimization model that, unlike the great majority of past emergency evacuation and planning research, takes into account a variety of driver, evacuation route, and traffic variables. In a subsequent study, *Dulebenets et al. (2019)* developed a mixed-integer programming strategy with the intention of reducing the overall evacuation duration. The primary purpose of the aforementioned work was to develop an enhancement approach and resolution algorithms for allocating catastrophe survivors to evacuation routes and crisis accommodation. *Dulebenets et al. (2019)* concluded that for large-scale issue situations, heuristic techniques were shown to be more promising than exact optimization algorithms. In contribution to improving emergency evacuation efficiency considering PWDs, several statistical models are proposed by *Dulebenets et al. (2019)* to comprehend the key influencing factors affecting the evacuation process. Their models comprehended various characteristics of drivers, traffic, and evacuation route with driving conditions. Both a driving simulator and actual emergency evacuation situations were used to collect data for their study. Age was revealed to be a statistically important factor affecting the driving capacity of people during an emergency evacuation, according to the findings. Younger people tended to drive faster and change lanes more frequently along the evacuation route (especially males) *(Dulebenets et al., 2019)*.

The majority of the aforementioned studies included automobiles in their simulation models, whereas only a few examined evacuations by special needs vehicles and public transportation. Nevertheless, transit-based evacuation planning only benefits PWDs who are able to use public transportation. PMA must have access to specialized emergency evacuation vehicles. Also, the above-mentioned studies consider that people without cars and mobile PWDs who need to go to public shelters will congregate in designated areas. Immobile PWDs, in other words PMA, will require special vehicles to pick them up, mainly from hospitals and senior care homes. Moreover, emergency evacuation vehicle operations in the network may not be as successful as projected due to numerous challenges such as traffic congestion and mishaps. As a result, emergency evacuation route planning is needed for PMA, considering traffic and road condition related criteria. In the context of evacuation planning for the disabled population, the identification and establishment of dedicated evacuation routes are crucial, given the time constraints and urgent requirements of those who require continuous emergency care. To ensure the safety and well-being of these vulnerable individuals, prompt and effective evacuation becomes crucial. By designating routes tailored to the requirements of disabled individuals, the evacuation process can be streamlined, reducing the amount of time required for them to reach safe areas or medical facilities. This approach recognizes the urgency of their situation and ensures that the evacuation procedure is tailored to their specific needs. Therefore, the identification of dedicated evacuation routes not only improves the overall efficacy of evacuation planning, but also demonstrates a commitment to safety and prompt assistance for PMA in emergency situations.

To fill the gap, this study adopts Multi-Criteria Decision Analysis (MCDA) approach for emergency evacuation route planning of PMA. From a conceptual and practical standpoint, structuring problems for MCDA have received a lot of attention in the last 20 years. Indications of this trend include an increasing number of published articles that use both a formal strategy for problem structuring and an analytical approach to MCA *(Marttunen and Belton, 2017)*. Methodologically speaking, the following section articulates the ways in which MCDA methods have been used as a means to solve some of the problems considering multiple decision making criteria in previous studies.

In the field of information theory, the Entropy Weight Method (EWM) is a widely used and extensively researched information weight model. For Example, an in-depth analysis of Shahu Lake's water quality was conducted by *Wu et al. (2017)*, providing decision-makers with important data on the lake's current water quality. *Yu et al. (2009)* investigated Gucheng Lake's water properties, including spatial distribution, eutrophication and health using the EWM method. Additionally, based on the EWM, *Zhang and Wang (2014)* in China's Chongqing metropolis, employed the EWM to analyze stress variables and the efficacy of water management systems. MCDA methods have been created to tackle real-world decision issues in a variety of ways, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), when implemented on different problems has consistently demonstrated impressive results. A few of the areas TOPSIS is used in are Design Engineering, Manufacturing Systems, Water resources management and Chemical Engineering *(Behzadian et al., 2012)*. To support the fire evacuation strategy, *Chanthakhot and Ransikarbum (2021)* developed a simulation model which integrated the position of assembly points assessed by using the MCDA approach, based on the integrated EWM and TOPSIS application. Mei and Xie (2017) introduced a Multi-party decision system in their study for Underground station evacuation strategy. In their study they used an improved TOPSIS method for evacuation strategy selection for various strategies considered *(Mei and Xie, 2017)*. The authors of another study *Mojtahedi et al. (2021)* constructed a disaster and emergency management index for hospitals, by evaluating the major characteristics related to the index using the TOPSIS as an MCDA technique. Moreover, many researchers have combined EWM and TOPSIS methods in the following manner. Using EWM, the objective relative importance (weights) of the assessment factors are computed, and a TOPSIS algorithm is used to rank a subset of practical choices. For example, *Huang (2008)* combined EWM and TOPSIS method to select an optimal information system. In another study using the EWM and TOPSIS technique, *Wu et al. (2021)* created an assessment framework for evaluating the safety of commuter rail station operations. In their study, a total of five different categories of first-level safety indexes and sixteen different types of second-level safety indexes are evaluated and ranked *(Wu et al., 2021)*. Furthermore, *Liu et al. (2021)* did an assessment of provincial waterlogging risk by investigating the flood control and risk reduction capabilities of 31 Chinese provinces using an entropy weight, TOPSIS application with PCA optimization model, and screened 25 assessment indicators *(Liu et al., 2021)*.

A novel aspect of this study is the application of a hybrid process of EWM in combination with cloud optimization and TOPSIS approach to the problem of selecting an emergency evacuation route for PMA. This research integrates cloud model optimization in between EWM and TOPSIS method to optimize and combine objective and subjective weights. Objective weights are obtained using EWM and subjective weights are given by practicing transportation planners and emergency evacuation managers. Hence, this research develops a model that integrates Entropy Weight, Cloud Optimization, and TOPSIS for selecting emergency evacuation routes for PMA, considering multiple traffic and road condition related criteria.

2.3 Methodology

This Study develops a route selection model to elect the best routes for emergency evacuation planning of PMA. The modeling framework comprises several components that generate the weights for road conditions and traffic related criteria. The objective and subjective weights are optimized, and the optimal evacuation routes are generated. Figure 2-1 provides an integrated framework demonstrating all the critical components to aid in the development of the optimal emergency evacuation routes to evacuate PMA from hospitals and senior care centers on the Halifax peninsula.

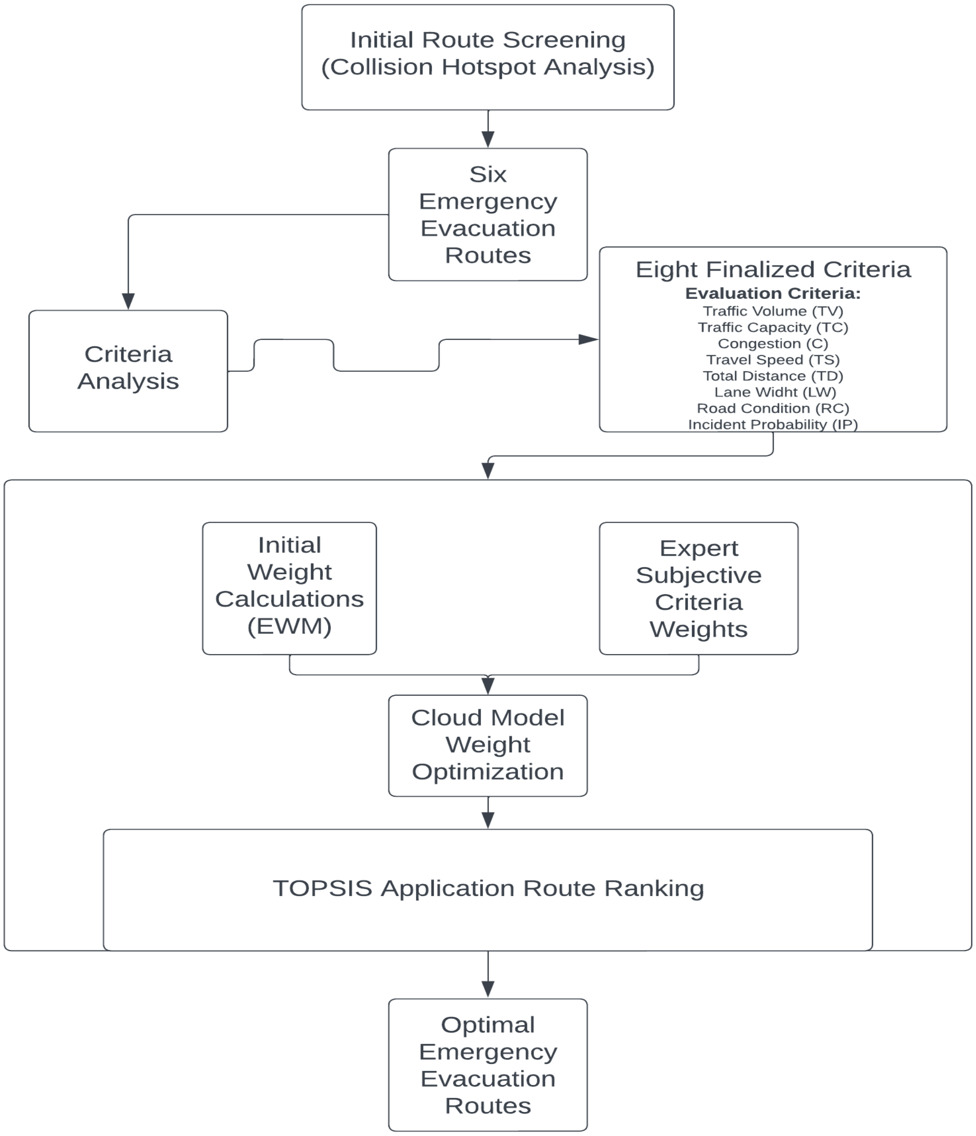

Figure 2-1: Conceptual Framework to Select Optimal Evacuation Routes for Evacuation of PMA

The methodology of this study is as follows: (1) Initial evacuation route screening of Halifax peninsula by performing collision hotspot analysis; (2) Six distinct evacuation routes are chosen to perform the MCA to produce the optimal evacuation routes; (3) The analysis of criteria is conducted to determine the factors pertaining to traffic and road conditions that have an impact on emergency evacuation operations; (4) EWM is used for initial criteria weight calculations; (5) Subjective criteria weights are obtained from the experts; (6) Cloud model optimization is used to combine the objective and subjective weights to generate the optimal criteria weights; (7) Optimal weights are used in the TOPSIS application to rank the routes for evacuation of PMA. This study considered Halifax Peninsula for emergency evacuation route selection for PMA, figure 2-2 shows the study area map.

Figure 2-2: Study Area Map

2.3.1 Initial Emergency Evacuation Route Screening

In this study, collision hotspot analysis for Halifax peninsula is performed using ArcGIS. The collision data used are from the years 2007 to 2011. Collision hotspot analysis was chosen for initial route screening due to evacuation routes ideally needing to have minimal incidents probability. Also, traffic collisions involving PMA have high risk of casualties compared to able-bodied individuals. Collision hotspot analysis gives an overview of high probability incident locations within the peninsula. Moreover, timely evacuation for PMA is of paramount importance. Since Halifax has historically narrow roads and limited entry/exit points from the peninsula, studies suggest that slight disruption such as a traffic collision can cause major traffic congestion on the road network *(Khan and Habib, 2018)*. In this manner six best routes are chosen which have less incident probability for MCA of optimal route selection for emergency evacuation.

2.3.2 Traffic and Road Condition Related Criteria Analysis

Many elements must be considered while evacuating PMA using emergency vehicles in cities. Several essential traffic and road condition related elements have an impact on the evacuation process. Of these elements, some have direct impact on whether an evacuation route is optimal to be used, while others have a considerable impact on the time it takes to safely evacuate the PMA. The following criteria were chosen as the basic influencing components for evaluating the emergency evacuation routes based on real operations of emergency evacuation and the opinions of practitioners of transportation planning: (1) Traffic Volume (TV); (2) Traffic Capacity (TC); (3) Congestion (C); (4) Travel Speed (TS); (5) Total Distance (TD); (6) Lane Width (LW); (7) Road Condition (RC); (8) Incident Probability (IP). Benefit criterion and cost criterion are two types of criteria. There is a positive impact on the result when using benefit criteria and a negative impact when using cost criteria. For example, in this case travel speed is benefit criteria, as a route with high travel speed will result in quick evacuation of PMA.

2.3.2.1 Traffic Volume (TV)

The number of cars travelling in a section of a lane, a direction, or a highway over a period of time is referred to as traffic volume and is measured in terms of cars per unit of time. The volume of traffic on the designated evacuation route is crucial to consider during the evacuation of PMA, as it has an immediate impact on the effectiveness and timeliness of their evacuation. A high volume of traffic can cause congestion and delays, which can considerably impede the progress of evacuation efforts and delay the whole evacuation operation. For the purposes of this study, initially traffic volume is taken as Annual Average Weekday Traffic (AAWT). Using weekday traffic will give a more realistic traffic volume idea than weekends, as weekend traffic volume tends to be low. Considering that the traffic volume increases significantly on the road network during the disaster evacuation scenario, the total AAWT is calculated for the 6 routes. Next, Maximum Traffic Volume (MTV) possible on the road network of Halifax peninsula is calculated using the Average Vehicle Occupancy Rate (AVOR) of 1.221 and total population of the HRM (HRM, 2022). Finally, MTV is assigned to each route by the percentage share of AAWT. The MTV is used for the MCA process. It is defined as a cost criterion, as more traffic volume on a route can result in more traffic on the road increasing the probability of collisions, congestion, and delays, and is denoted as TV. To calculate MTV for this study, traffic volume data was obtained from HRM open data sources *(HRM, 2022)*.

2.3.2.2 Traffic Capacity (TC)

Capacity is the maximum number of vehicles per hour (v/h) that may operate safely on a highway facility at any given time, given the existing roadway, traffic, and control conditions, and expressed as vehicles per hour (v/h). To calculate traffic capacity, every route is treated as signalized arterial. The equation used to calculate capacity is $Capacity = \frac{g}{c} * lanes * 2{,}200$ (g/c is 0.45 for arterials). Traffic capacity is defined as a benefit criterion, as high traffic capacity means higher flow of traffic resulting in less congestion.

2.3.2.3 Congestion (C)

Congestion level is defined as volume to capacity ratio (V/C). Volume used to obtain V/C ratio is the design hourly volume (DHV) taken from AAWT using the following equation $DHV = K * AAWT$, K=0.1. This is defined as a cost criterion, as more congestion on a route will result in delays in evacuation process.

2.3.2.4 Travel Speed (TS)

In the context of this study, the road's design speed, rather than its posted speed limit, is selected as the determinant of travel speed. Under an evacuation scenario, emergency vehicles will travel at the maximum design speed of the road, rather than the indicated speed limit. The speed at which vehicles can travel on the road safely and efficiently has an immediate effect on the duration of the evacuation and the prompt arrival of assistance for disabled individuals. This criterion is defined as a benefit attribute. High travel speed of the route will result in the faster evacuation of the PMA.

2.3.2.5 Total Distance (TD)

Total Distance is the total length of a route measured in kilometers (Km). During the evacuation procedure for PMA, it is essential to consider the total distance of the designated evacuation route. The distance traveled has a direct bearing on the time required for evacuation and the amount of physical exertion that individuals with disabilities may endure. This criterion is defined as a cost criterion, as a longer route length means evacuation vehicles will take longer time to evacuate PMA safely.

2.3.2.6 Lane Width (LW)

The width of a lane, or "Traveled Way," is the distance in meters between the centerline of the road and its edge markers (if present) or the edge of the road's surfacing material, measured in meters (m). Wider lanes will result in higher travel speed for emergency evacuation vehicles. Therefore, this criterion is defined as a benefit criterion.

2.3.2.7 Road Condition (RC)

Road condition is defined in terms of pavement condition encountered by the user. Pavement condition is considered as the quality of roads. For example, pavement condition considers pavement roughness, cracks, ruts, potholes, and patches. For this study a road condition index is established. "Good" roads have only slight signs of wear and tear, "Medium" roads have more significant deterioration and require frequent patching, and "Bad" roads have enormous potholes and deep cracks that are quite unpleasant to drive over at low speeds. The road condition index is defined on the following scale: Good = 3.0-4.0, Medium = 2.0-3.0, and Poor = 1.0-2.0. This is defined as a benefit criterion, as better road condition results in less incident probability and a safer evacuation process.

2.3.2.8 Incident Probability (IP)

In this study incident probability is referring to the collision probability of the selected evacuation routes. It is taken from the collision hotspot analysis performed, for the initial route screening process. Incident probability values are taken in a manner that, if the route is significantly passing through hotspots, it will have high percentage (%) and vice versa. This is defined as a cost criterion, considering that roads with high incident probability are considered unsafe.

2.3.3 Initial Criteria Objective Weight Analysis

Criteria weight is defined as the comparative relevance of a selection criterion relative to other selection criteria. It is very important to have the criteria weights for the analysis of the optimal emergency evacuation route selection. There are a variety of strategies for establishing the weights of criteria, which can be classified as subjective or objective. The subjective approach selects weights exclusively based on the considerations or judgments of decision makers, whereas the objective approach selects weights based on mathematical computations that eliminate decision makers' subjective judgement information. Given the advantages and disadvantages of both subjective and objective procedures, it appears that an integrated or combined method for computing criteria weights is preferred. An integrated or combined method for computing criteria weights is preferred due to its ability to address the limitations of both subjective and objective procedures. Subjective methods, such as surveys and expert opinions, provide valuable insights based on real-world experiences but can be influenced by individual biases and lack precision. On the other hand, objective methods, like information entropy, offer a more systematic approach but may overlook the subjective relevance of criteria in real operations. By combining both approaches, researchers can benefit from the richness of real-world expertise while still ensuring a more comprehensive and robust evaluation process, leading to better-informed decisions in complex scenarios such as evacuation route planning. In this study criteria weights are established both objectively and subjectively. Objective and subjective weights are combined to obtain the optimal set of criteria weight which is used to select the optimal emergency evacuation routes. Before calculating objective criteria weights, the original road attribute data is standardized.

2.3.3.1 Original Data Standardization

Initially, data are normalized and qualitatively enhanced, and the primary route parameters are modified to fit within a restricted range. The original data are changed into a quantity without dimensions, to be compared across several units of measure. Due to the constraints imposed by the study's benefit and cost criteria, the original data has been normalized using the Max-Min Normalization method, the conversion formula is as follows:

$$\underset{(Benefit)}{x\ norm} = \frac{y-y_{min}}{y_{max}-y_{min}} \qquad \underset{(Cost)}{x\ norm} = \frac{y_{max}-y}{y_{max}-y_{min}} \tag{1}$$

Here, y denotes the parameter's original data value y_{min} refers to the minimum value of the parameter, y_{max} refers to the maximum value of the parameter, and x refers to the normalized value of the original data matrix.

2.3.3.2 Objective Weight Determination using Entropy Weight Method (EWM)

In this study, the weight of each influencing criterion is calculated using the entropy weight approach, involving the information entropy concept. According to information entropy, the entropy value of a particular component can be used to characterize the degree to which that component is discrete. If a factor's information entropy value is low, it has a high degree of discreteness and a strong impact on the overall assessment (i.e., weight), whereas if the factor's value is uniform across the board, it has no impact on the evaluation *(Zhu and Yan, 2020)*. As a result, the information entropy tool can be used to establish the relative relevance of each criterion in order to provide a foundation for a comprehensive assessment of several elements. The Entropy Weight Method (EWM) used in this study assigns weights based on the uncertainty in data, utilizing information entropy to measure the discreteness of each criterion. To optimize these weights with subjective input from real-world operations, the study employs the Cloud Model Optimization approach, allowing for a more comprehensive and informed assessment of each criterion's impact on the overall evaluation. The weight determination process using EWM is a three-step process.

Step 1: Based on the standardized data, the normalization of measured values is the first stage. The p_{ij} stands for the standardized value of the i_{th} index in the j_{th} sample, and is expressed as:

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \tag{2}$$

Step 2: Next is to calculate the information entropy value E_j, which is defined as:

$$E_j = -K \sum_{i=1}^{n} p_{ij} \ln (p_{ij}) \tag{3}$$

where K is defined as $K = 1/\ln(n)$. For the above steps, n stands for the alternative routes. For simplification of the calculation in EWM, $p_{ij} \cdot \ln p_{ij} = 0$, when $p_{ij} = 0$.

Step 3: This step is to calculate the criteria weight w_j in the following manner:

$$w_j = \frac{1-E_j}{\sum_{j=1}^{m}(1-E_j)} \tag{4}$$

above, m indicates different road and traffic related criteria.

2.3.4 Cloud Model Objective/Subjective Weight Optimization

The degree of value divergence is reflected in the cloud model's entropy. Our findings indicate that the criterion weight calculation technique can be improved by applying cloud entropy in order to optimize the EWM weights. The enhanced computation approach is employed to generate a distribution of weights that accurately represent the significance of each criterion by incorporating both subjective and objective weights, and the cloud model serves to process the subjective assessments of transportation planners. For the purpose of this study, we ran a survey to collect subjective weights for each criterion.

2.3.4.1 Definition of the Cloud Model

The definition of cloud model is if U is a universal set described by exact numbers and C is the corresponding qualitative concept in relation to U. If there is a number that exists as $x \in U$, which randomly realizes the concept of C, and the certainty degree of x for C, i.e. $z(x) \in [0, 1]$, is a random value with a tendency of stabilization *(Yao, 2012)*:

$$z(x) : U \rightarrow [0, 1] \ \forall x \in U \ x \rightarrow z(x),$$

If this is the case, the distribution of x on U can be defined as a cloud, with each unique x being a cloud droplet, noted Drop (x, z).

2.3.4.2 Descriptive Cloud Model Statistics

There are three descriptive statistics applied to cloud models. The cloud model is represented by the letter "C". The three statistics are described as follows:

Key Statistics	**Description**
Ex – Mean Value	• The statistical mean and the mean value of the cloud model are identical.
En – Entropy	• The level of randomization given to the cloud droplets utilized in the simulation determines the entropy. It symbolizes the uncertainty of droplet formation of the cloud.
He – Hyper-entropy	• Supplementary statistic derived from entropy, represents both the uncertainty of entropy and the randomness of the cloud model.

2.3.4.3 Backward Cloud Generator

Figure 2-3 depicts the Backward Cloud Generator (BCG), the method by which a list of precise quantities is converted to qualitative associations. The three descriptive statistics listed above are used to do further analysis and calculations, which is the BCG's core transformation premise. In this situation, we enter the precise scores given by the transportation planners, assess the score's discreteness using BCG from key descriptive statistics, and using the evaluation's conclusion as a weighting benchmark.

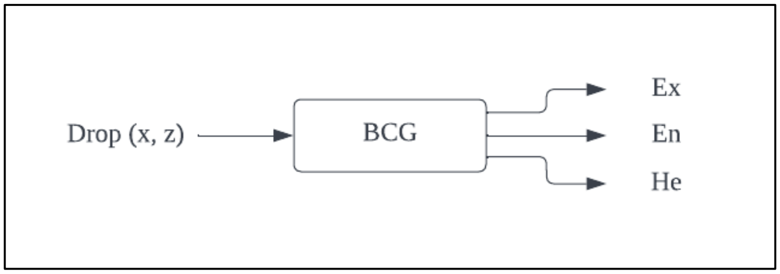

Figure 2-3: Backward Cloud Generator

We polled transportation planners and emergency evacuation managers through the PMA research network to determine how road and traffic condition-related criteria influence the selection of emergency evacuation routes by assigning subjective scores, and using their professional knowledge and real-world experiences. With a possible range between 0 and 100, the score is an integer multiple of 5. The greater the significance of a criterion, the better the score. The experts participating in this research are seasoned professionals with a wealth of experience in emergency evacuation management and transportation planning, each possessing a minimum of 10 years of expertise in their respective fields. Through the "Evacuation Planning for People with Disabilities" research network, transportation planners and emergency evacuation managers were polled to gather their valuable insights. The experts were asked to provide subjective scores (ranging from 0 to 100) for each of the eight criteria: Traffic Volume (TV), Traffic Capacity (TC), Congestion (V/C), Travel Speed (TS), Total Mileage (TM), Lane Width

(LW), Road Condition (RC), and Incident Probability (IP). The experts participating in this research were informed that the objective weights have already been assigned to the eight criteria. The scores, represented as integer multiples of 5, reflected the perceived impact of each criterion on route selection for evacuation vehicles, based on their extensive real-world experiences. The subjective scores collected from these respected practitioners will be combined with the predetermined objective weights to derive the optimized weights. These optimized weights will then be integrated into the ongoing development of a Route Selection Model specifically designed for evacuation planning for PMA, enabling the research to benefit from their valuable professional perspectives and expertise. The scores are examined using a backward cloud generator in the following manner.

The mean value (Ex) of the score table is calculated as:

$$Ex = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{5}$$

where x_i is defined as the subjective score assigned by the practitioners.

The formula for determining the center distance (CD) is as follows:

$$CD = \frac{1}{n} \sum_{i=1}^{n} |x_i - Ex| \tag{6}$$

To determine the data's cloud entropy (En), we use the formula:

$$En = \sqrt{\frac{\pi}{2}} \times \frac{1}{n} \sum_{i=1}^{n} |x_i - Ex| \tag{7}$$

To determine the variance of the data (S^2), we use the formula:

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - Ex)^2 \tag{8}$$

The Hyper-Entropy of the score table (He) is calculated as:

$$He = \sqrt{S^2 - En^2} \tag{9}$$

2.3.4.4 *Cloud Model Weight Optimization Process*

Based on the cloud entropy calculation results and the criteria weights obtained by EWM. the optimized set of criteria weight considering both objective and subjective weight is calculated as follows:

$$W_j = \frac{1}{2} \cdot \left[\frac{Ex_i}{\ln(1+En_i)+1} \cdot \frac{1}{\sum_{i=1}^{n} \frac{Ex_i}{\ln(1+En_i)+1}} + w_j\right] \tag{10}$$

Here, we compute and adjust the weight of each factor. The result is combined with the EWM obtained weights (w_j) in section 3.3. Standard distribution modifications are made to the weights of the criteria in this section, and Ex is processed based on the degree of dispersion level of En. In general, the average cloud value increases as the significance of a particular criterion increases. A high cloud entropy indicates widespread disagreement among experts over the significance of this factor, then the factor's weight should be reduced. The less cloud entropy there is, the fewer practitioner disagreements there will be on this factor; hence, it should be given greater weight. Practitioner disagreements in opinions regarding certain criteria indicate the uncertainty of the factor's importance in the evaluation process. To address this uncertainty, criteria with higher practitioner agreement are assigned greater weight, as their significance is more evident and less subject to varying interpretations.

2.3.5 TOPSIS Application

The core concept of TOPSIS, a utility-based strategy, whose basic premise is the estimated distance between the negative ideal solution (NIS) and the positive ideal solution (PIS). According to the number of criteria in the problem, the approach calculates distances using the n–dimensional Euclidean distance *(Çelikbilek and Tüysüz, 2020)*. The reason TOPSIS application is employed in this study is its strong suitability in handling multiple criteria, including both cost and benefit criteria. By establishing the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) Planes, the TOPSIS application effectively accommodates the diverse nature of our study's criteria, making it the most suitable approach for route ranking that considers both cost and benefit aspects. In this study, the optimized set of criteria weights obtained in section 2.3.4 were used to generate the optimal routes for emergency evacuation of PMA. Steps in TOPSIS approach are as follows:

Step 1

Given the benefit and cost criteria constraints, the Max-Min Normalization approach is employed in this study to standardize the original data, as illustrated in section 2.3.3. The standardized data matrix (x_{ij}) is denoted as (m_{ij}) and used in TOPSIS analysis. When applied to the original data matrix, Max-Min Normalization reduces the lowest criterion value to 0 and the highest criterion value to 1 for the benefit criterion, and vice versa for the cost criterion.

Step 2

The standardized data matrix (m_{ij}) goes through a secondary TOPSIS standardization process, and the secondary matrix is set as (r_{ij}). The TOPSIS standardization process is as follows:

$$r_{ij} = \frac{m_{ij}}{\sqrt{\sum_{j=1}^{M} m_{ij}^2}} \tag{11}$$

Next, the weighted normalized decision matrix (V_{ij}) is constructed, using the optimized criteria weights (W_j) calculated in section 3.4. The process is as follows:

$$V_{ij} = W_j r_{ij} \tag{12}$$

Step 3

PIS and NIS are computed following the calculation of (Vij). The PIS plane consists of the six possible routes with the Maximum attainable value in the benefit criteria's matrix V and the minimum attainable value in the cost criteria's matrix V. The NIS plane is produced in a similar manner as the PIS plane, by selecting the minimum value of the benefit criterion and maximum value of the cost criterion. The steps involved in acquiring PIS and NIS are as follows, with I' denoting the benefit criteria and I" denoting the cost criteria:

$$A^{+} = \left\{V_{ij}^{+}1, \dots\dots\dots V_{n}^{+}\right\} = \left\{\left(\max V_{ij} \mid i \ \in I'\right), \left(\min V_{ij} \mid i \in I''\right)\right\} = PIS \qquad (13)$$

$$A^{-} = \left\{V_{ij}^{-}1, \dots\dots\dots V_{n}^{-}\right\} = \left\{\left(\min V_{ij} \mid i \ \in I'\right), \left(\max V_{ij} \mid i \in I''\right)\right\} = NIS \qquad (14)$$

Step 4

In this step, the Euclidean distance for each potential route is calculated. The optimal choice among the six alternatives is always the one that advances towards the PIS plane and retreats from the NIS plane. For each viable option, the entire distance between the PIS plane and the NIS plane must be calculated. The mathematical formula for calculations is as follows:

$$D_j^{+} = \sqrt{\sum_{i=1}^{n} (V_{ij} - V_j^{+})^2} \qquad (15)$$

$$D_j^{-} = \sqrt{\sum_{i=1}^{n} (V_{ij} - V_j^{-})^2} \qquad (16)$$

where D_j^+ indicates the distance between the PIS plane and each emergency evacuation route, and D_j^- represents the distance between the NIS plane and each emergency emergency evacuation route.

Step 5

Once the Euclidean distance is obtained, the relative closeness to the ideal solution P_i^* must be found. The process is as follows:

$$P_i^* = \frac{D_j^-}{D_j^+ + D_j^-} \tag{17}$$

This equation yields a score that reflects how near an alternative is, or the relative closeness to the best solution. A higher score for an option suggests that it approximates the optimal response more closely. For the decision making problem at hand, the route with the highest relative closeness score will be the best route and vice versa.

2.4 Results and Discussion

2.4.1 Initial Route Selection

The collision hotspot analysis for Halifax peninsula is performed using collision data from 2007 to 2011. Figure 2-4 shows the resulting collision hotspot analysis map.

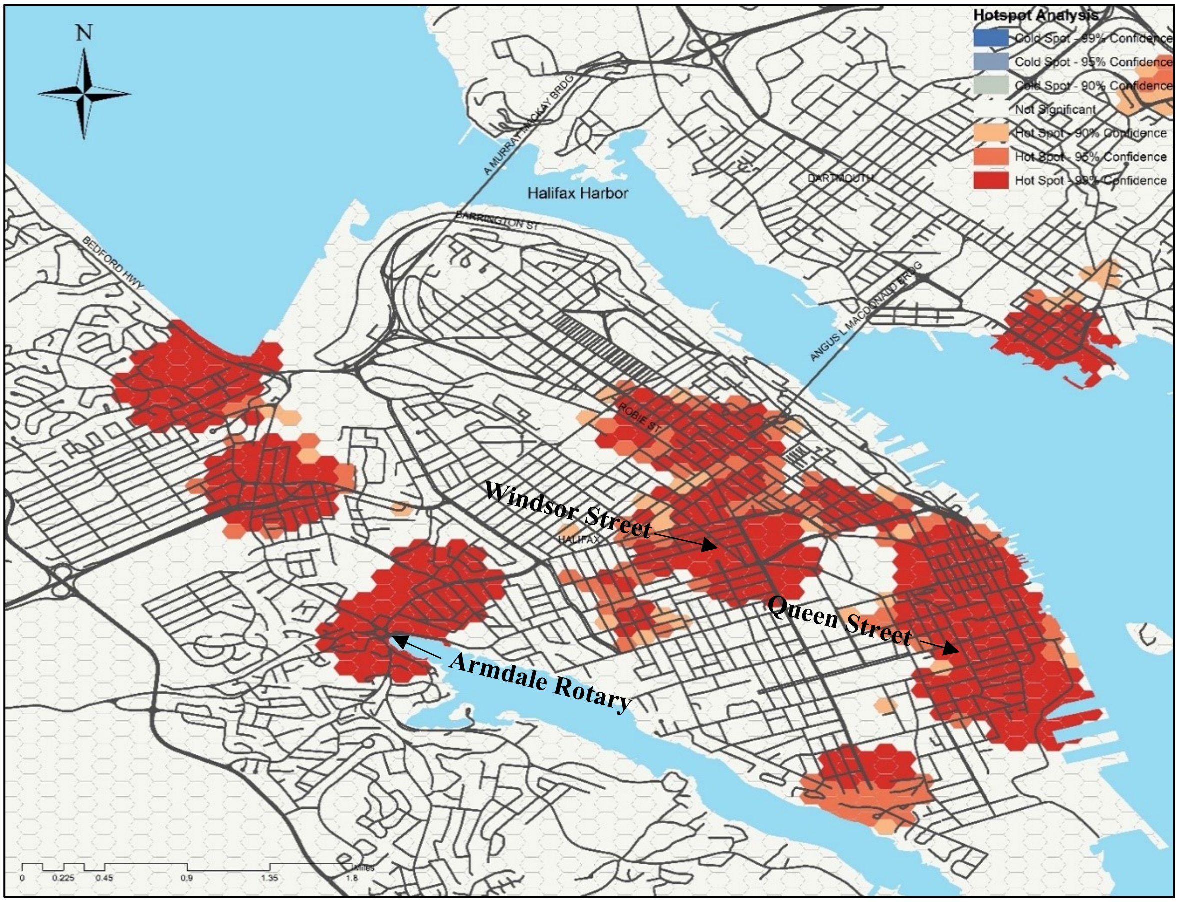

Figure 2-4: Map Visualizing Incident Probability Around Halifax Peninsula

As illustrated in figure 2-4, areas around Windsor Street, Queen Street and Armdale rotary are highly prone to collisions. After performing the collision hotspot analysis, six routes were chosen to perform an MCA for emergency evacuation route selection. Figure 2-5 below shows the six routes selected after the collision hotspot analysis was performed.

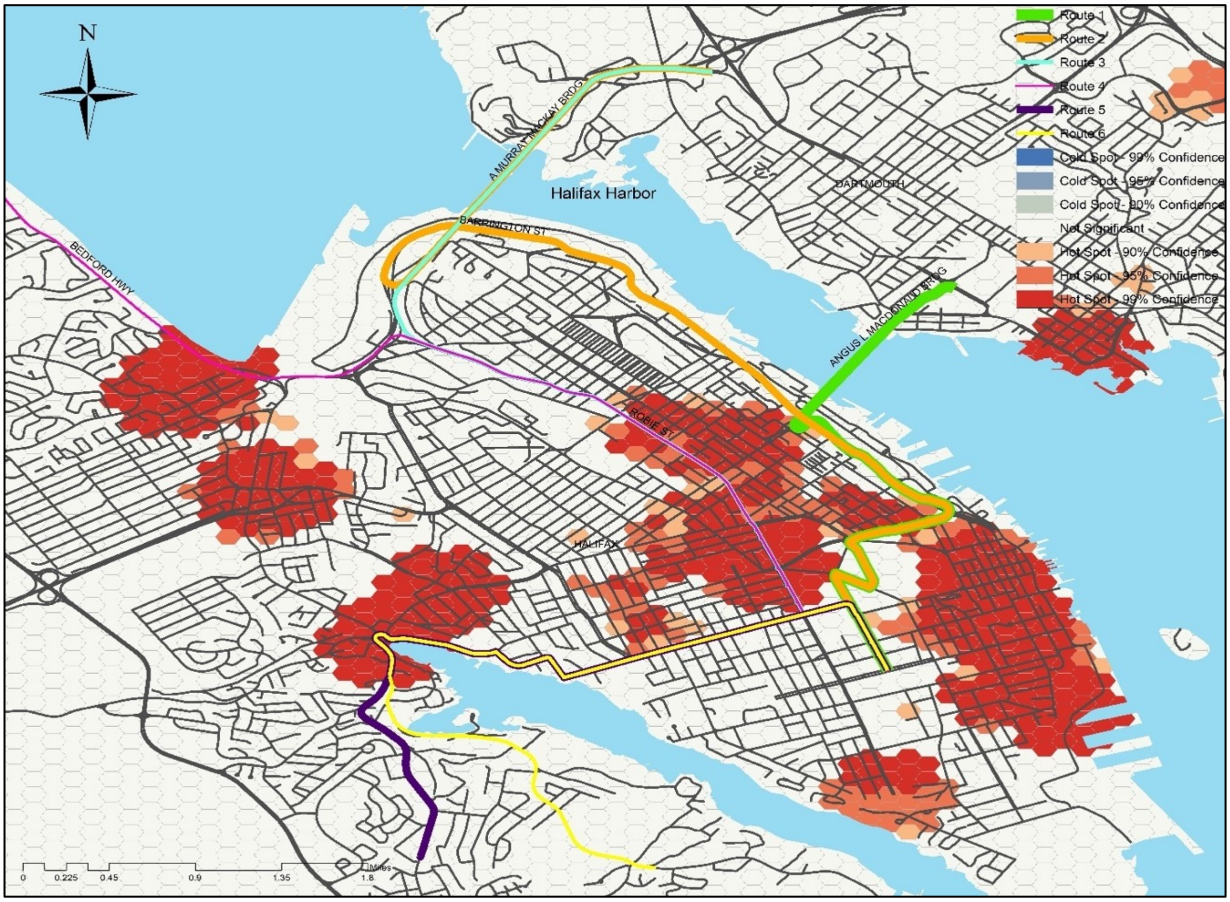

Figure 2-5: Map of Six Routes with Minimal Incident Probability Selected for MCA

As shown in figure 2-5, six routes with the lowest probability of incidence are selected following the initial evaluation of routes using collision hotspot analysis. The section next discusses the criteria data for the above-selected routes for MCA and the standardization of the data for further analysis.

2.4.2 Criteria Analysis and Data Standardization

Based on actual emergency evacuation operations and the perspectives of transportation planning practitioners, this study determines the eight fundamental influencing components for evaluating emergency evacuation routes, which are as follows: (1) Traffic Volume (TV); (2) Traffic Capacity (TC); (3) Congestion (C); (4) Travel Speed (TS); (5) Total Distance (TD); (6) Lane Width (LW); (7) Road Condition (RC); (8) Incident Probability (IP). Table 2-1 below shows the criteria data values for six chosen routes for the MCA process.

Table 2-1: Alternative Route Criteria Values

Routes	TV	TC	C	TS	TD	LW	RC	IP
	(MTV)	(v/h)	(V/C)	(km/h)	(km)	(m)	(Quan)	(%)
R1	**71712**	**1485**	**0.82**	**80**	**5.20709**	**3.6**	**4**	**30**
R2	**80937**	**1980**	**0.92**	**80**	**10.0807**	**3.8**	**4**	**30**
R3	**52649**	**1980**	**0.6**	**80**	**7.97563**	**3.7**	**3.5**	**80**
R4	**61694**	**2475**	**0.71**	**80**	**8.61085**	**3.4**	**3.5**	**80**
R5	**46631**	**1000**	**0.54**	**60**	**6.02817**	**3.3**	**2.5**	**50**
R6	**46631**	**1000**	**0.54**	**60**	**6.93841**	**3.3**	**2.5**	**50**

As shown in table 1 above, R1 has a traffic volume of 71,712 MTV, a traffic capacity of 1485 v/h, a congestion ratio of 0.82, design travel speed of 80 km/h, total distance of 5.21 km, lane width of 3.6 m, good road condition with a score of 4 and an incident probability of 30%. R2, R3, R4, R5, and R6 also have corresponding values for the various parameters mentioned above. These values provide insights into the traffic characteristics, road conditions, and intersection performance for each route. Further analysis and interpretation can be performed based on these data points to evaluate and compare the efficiency, capacity, and overall performance of the different routes. Next the original road attribute data is standardized using equation (1). Equation (1) uses the data from the following original data matrix:

$$y = \begin{pmatrix} 71712 & 1485 & 0.82 & 80 & 5.20709 & 3.6 & 4.0 & 30 \\ 80937 & 1980 & 0.92 & 80 & 10.0807 & 3.8 & 4.0 & 30 \\ 52649 & 1980 & 0.60 & 80 & 7.97563 & 3.7 & 3.5 & 80 \\ 61694 & 2475 & 0.71 & 80 & 8.61085 & 3.4 & 3.5 & 80 \\ 46631 & 1000 & 0.54 & 60 & 6.02817 & 3.3 & 2.5 & 50 \\ 46631 & 1000 & 0.54 & 60 & 6.93841 & 3.3 & 2.5 & 50 \end{pmatrix}$$

Descriptive statistics of the initial data are presented in table 2-2, which is also utilized by equation 1 to produce a normalized data matrix.

Table 2-2: Descriptive Statistics of the Original Data

Criteria	Maximum	Minimum	Mean	Standard Deviation
TV	**80937**	**46631**	**60042.33**	**14070.432**
TC	**2475**	**1000**	**1653.33**	**595.077**
C	**0.92**	**0.54**	**0.69**	**0.157**
TS	**80**	**60**	**73.33**	**10.328**
TD	**10.08**	**5.20**	**7.47**	**1.781**
LW	**3.8**	**3.3**	**3.52**	**0.214**
RC	**4**	**2.5**	**3.33**	**0.683**
IP	**80**	**30**	**53.33**	**22.509**

After normalization process, the matrix is expressed as:

$$x_{ij} = \begin{pmatrix} 0.268903 & 0.328814 & 0.26315 & 1 & 1 & 0.6 & 1 & 1 \\ 0 & 0.664407 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0.824579 & 0.664407 & 0.84210 & 1 & 0.43192 & 0.8 & 0.666667 & 0 \\ 0.560922 & 1 & 0.55263 & 1 & 0.30158 & 0.2 & 0.666667 & 0 \\ 1 & 0 & 1 & 0 & 0.83152 & 0 & 0 & 0.6 \\ 1 & 0 & 1 & 0 & 0.64475 & 0 & 0 & 0.6 \end{pmatrix}$$

The subsequent sections utilize the aforementioned normalized original data matrix for objective criteria weights, optimized criteria weights, and the optimal route ranking procedure.

2.4.3 Determination of Objective Weights

The relative importance (weight) of each criterion is determined using the EWM method. The first step of EWM is to standardize data, so the EWM standardization procedure is applied to the normalized data. Table 2-3 displays the EWM-normalized values for each criterion for each alternative route.

Table 2-3: EWM Standardized Criteria Values

	P_{ij}							
	TV	**TC**	**C**	**TS**	**TD**	**LW**	**RC**	**IP**
R1	0.073	0.124	0.072	0.250	0.312	0.231	0.300	0.313
R2	1.000	0.250	1.000	0.250	1.000	0.385	0.300	0.313
R3	0.226	0.250	0.230	0.250	0.135	0.308	0.200	1.000
R4	0.153	0.376	0.151	0.250	0.094	0.077	0.200	1.000
R5	0.274	1.000	0.273	1.000	0.259	1.000	1.000	0.188
R6	0.274	1.000	0.273	1.000	0.201	1.000	1.000	0.188

Next, figure 2-6 shows the information entropy and objective weights for the road and traffic related criteria.

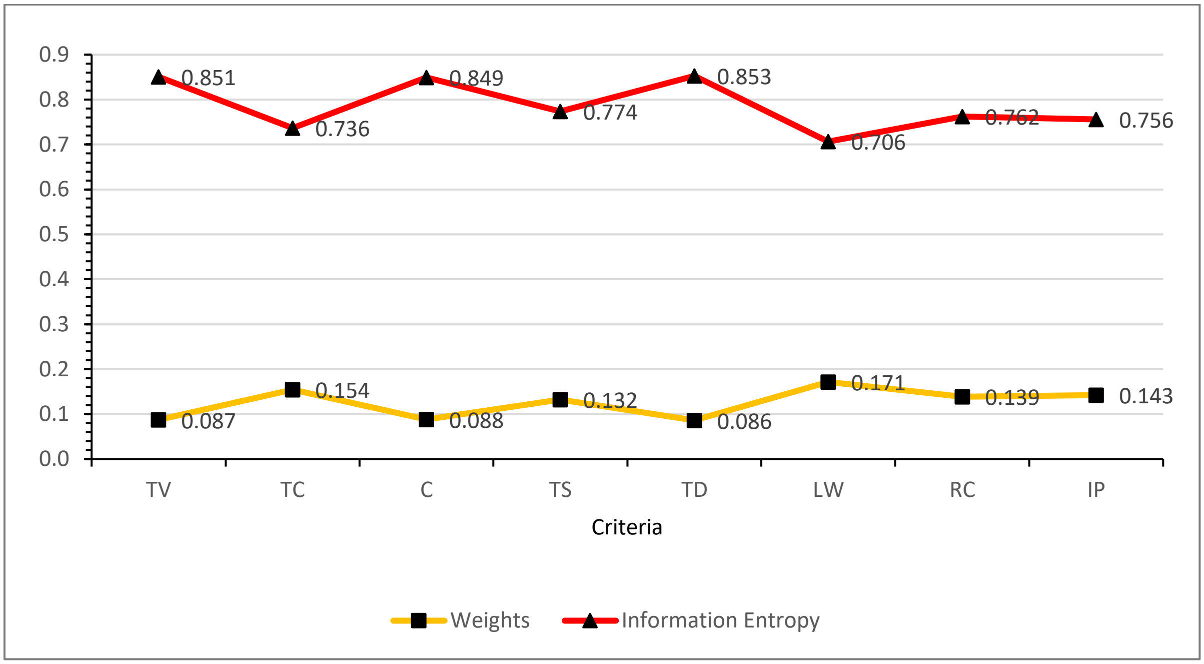

Figure 2-6: Information Entropy and Objective Criteria Weights

As illustrated in figure 2-6 LW, TC, IP, and RC criteria are given the highest objective weights, since emergency evacuation vehicles need to have wide lanes, high capacity, less incident probability and good condition roads to perform quick, and safe evacuation of PMA. It is also clear that the evaluation criterion has less weight the higher its information entropy. Hence higher weights are given to the criterion with less information entropy.

2.4.4 Objective/Subjective Weight Optimization

Through the PMA research network, a survey was conducted in this study to assign subjective scores to road and traffic conditions related criteria that affect emergency evacuation route selection process. Table 2-4 shows the scores given to each criterion by experts.

Table 2-4: Subjective Weights by Transportation Planners and Emergency Evacuation Workers

	Subjective Weights							
Expert	**TV**	**TC**	**C**	**TS**	**TD**	**LW**	**RC**	**IP**
1	60	85	75	80	95	65	80	80
2	80	85	70	90	90	60	95	75
3	90	75	70	90	95	65	95	75
4	75	70	85	85	90	55	80	90
5	75	65	65	70	95	70	90	80
6	80	75	85	95	90	65	95	75
7	65	80	75	85	95	65	90	70

The cloud model's detailed statistics (Ex, En, He) are calculated using BCG in this study. The Ex, En and He values are generated using the subjective weights given by practitioners for traffic and road condition related criteria. Table 2-5 below shows the detailed statistics of cloud model calculated using BCG.

Table 2-5: Key Statistics of Cloud Model

Ex	**Expected/Mean Value**
En	**Cloud Entropy**
He	**Hyper-entropy**

Statistics of Cloud Model			
Criteria	**Ex**	**En**	**He**
TV	75	8.95224	4.45616
TC	76.4286	7.41757	0.96542
C	75	7.16179	2.65369
TS	85	7.16179	3.92115
TD	92.8571	3.06934	1.5093
LW	63.5714	4.34823	1.92664
RC	89.2857	6.65024	1.00621
IP	77.8571	5.8829	2.42233

As indicated in table 2-5, practitioners showed significant disagreement over the subjective weights assigned to criteria TV, TC, C, and RC. The high value of En for these criteria indicates this. Similarly, the preceding data indicates that experts agreed on the subjective weights for criterion TD, LW, and IP because the En value for these criteria is low.

Based on the cloud entropy calculation results (Ex, En, He) and the criteria weights obtained by EWM, the optimized set of criteria weights considering both objective and subjective weights is calculated using Formula (10) and are shown in figure 2-7.

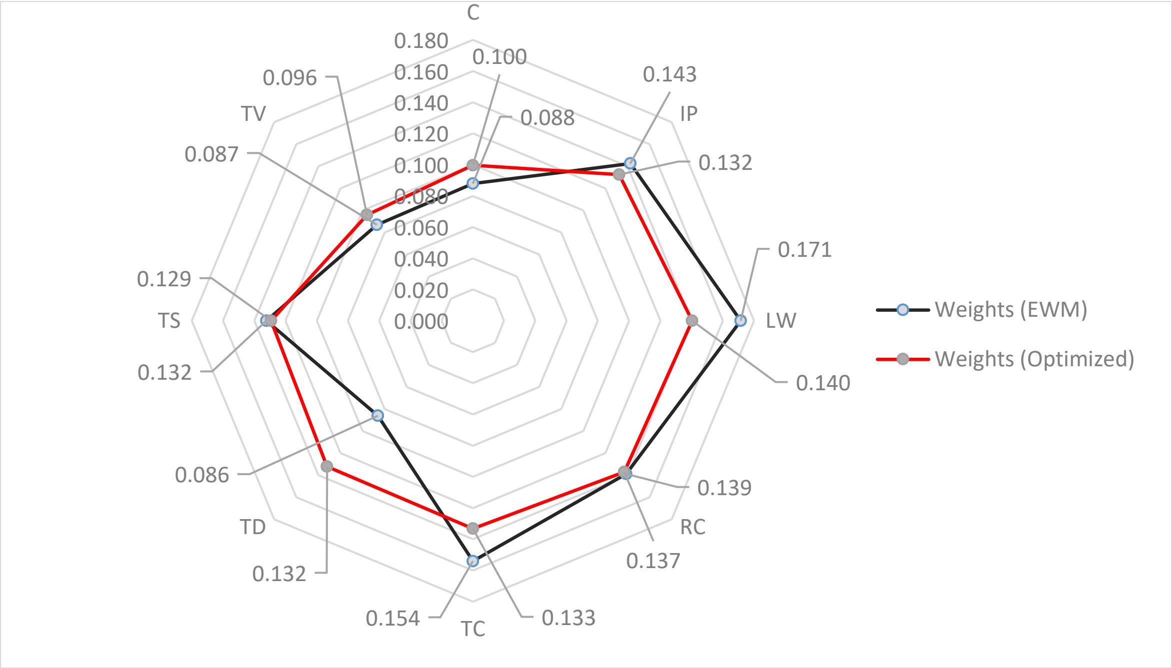

Figure 2-7: Subjective/Objective Optimized Criteria Weights

As illustrated in figure 2-7, LW, RC and TC are given the highest optimized weights, providing with the insight that the above mentioned criteria has a significant impact on selecting the optimal route for emergency evacuation of PMA. It can be noticed from the figure 2-7 that emergency evacuation managers had a strong disagreement with objective weights of the criteria TD, TC and LW. The emergency evacuation managers gave more weight to TD. The objective weight of TD is 8.6%, but the optimized weight increases to 13.2%. Similarly, optimized weight of TC and LW is less compared to the objective weight.

2.4.5 TOPSIS Application Optimal Route Ranking

In this study, the criteria weights are established both objectively and subjectively. EWM is used to derive objective weights, as opposed to the subjective weights provided by practicing transportation planners and emergency evacuation researchers. Then, using cloud model optimization, objective and subjective weights are combined to generate the optimal set of criteria weights, which is used to determine the optimal evacuation routes.

The following sections presents the TOPSIS application route ranking using only the EWM's objective weights. Following that, it will provide the route ranking using the optimal set of criteria weights produced by integrating objective and subjective weights. Finally, a comprehensive comparison of both route rankings is undertaken, as well as a comprehensive analysis of the characteristics and differences of each optimal route.

The standardized data matrix (x_{ij}) has resulted in section 4.2. The same data matrix is denoted as (m_{ij}) and used in TOPSIS analysis. The standardized data matrix m_{ij} is as follows:

$$m_{ij} = \begin{pmatrix} 0.26890 & 0.32881 & 0.26315 & 1 & 1 & 0.6 & 1 & 1 \\ 0 & 0.66441 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0.82458 & 0.66441 & 0.84210 & 1 & 0.43192 & 0.8 & 0.66667 & 0 \\ 0.56092 & 1 & 0.55263 & 1 & 0.30158 & 0.2 & 0.66667 & 0 \\ 1 & 0 & 1 & 0 & 0.83152 & 0 & 0 & 0.6 \\ 1 & 0 & 1 & 0 & 0.64475 & 0 & 0 & 0.6 \end{pmatrix}$$

The above-mentioned data matrix is then subjected to a further TOPSIS standardization process, and the second matrix is designated as (r_{ij}). The matrix (r_{ij}) after the TOPSIS standardization process is as follows:

$$r_{ij} = \begin{pmatrix} 0.15 & 0.23 & 0.15 & 0.5 & 0.65 & 0.42 & 0.59 & 0.61 \\ 0 & 0.47 & 0 & 0.5 & 0 & 0.70 & 0.59 & 0.61 \\ 0.47 & 0.47 & 0.48 & 0.5 & 0.28 & 0.56 & 0.39 & 0 \\ 0.32 & 0.71 & 0.31 & 0.5 & 0.195 & 0.14 & 0.39 & 0 \\ 0.57 & 0 & 0.57 & 0 & 0.54 & 0 & 0 & 0.36 \\ 0.57 & 0 & 0.57 & 0 & 0.42 & 0 & 0 & 0.36 \end{pmatrix}$$

The weighted normalized decision matrix (V_{ij}) is then built using the optimal criteria weights (W_j) using equation (12). The weighted normalized values for each criterion are shown in Table 2-6 below.

Table 2-6: TOPSIS Weighted Normalized Values

	Vij - Weighted Normalized Decision Matrix							
	TV	**TC**	**C**	**TS**	**TM**	**LW**	**RC**	**IP**
R1	0.0147	0.0310	0.0149	0.0646	0.0855	0.0590	0.0807	0.0803
R2	0.0000	0.0627	0.0000	0.0646	0.0000	0.0983	0.0807	0.0803
R3	0.0452	0.0627	0.0478	0.0646	0.0369	0.0786	0.0538	0.0000
R4	0.0307	0.0944	0.0314	0.0646	0.0258	0.0197	0.0538	0.0000
R5	0.0548	0.0000	0.0568	0.0000	0.0711	0.0000	0.0000	0.0482
R6	0.0548	0.0000	0.0568	0.0000	0.0551	0.0000	0.0000	0.0482

PIS and NIS are computed following the calculation of (Vij). Figure 2-8 illustrates the PIS and NIS planes obtained using equations (13) and (14).

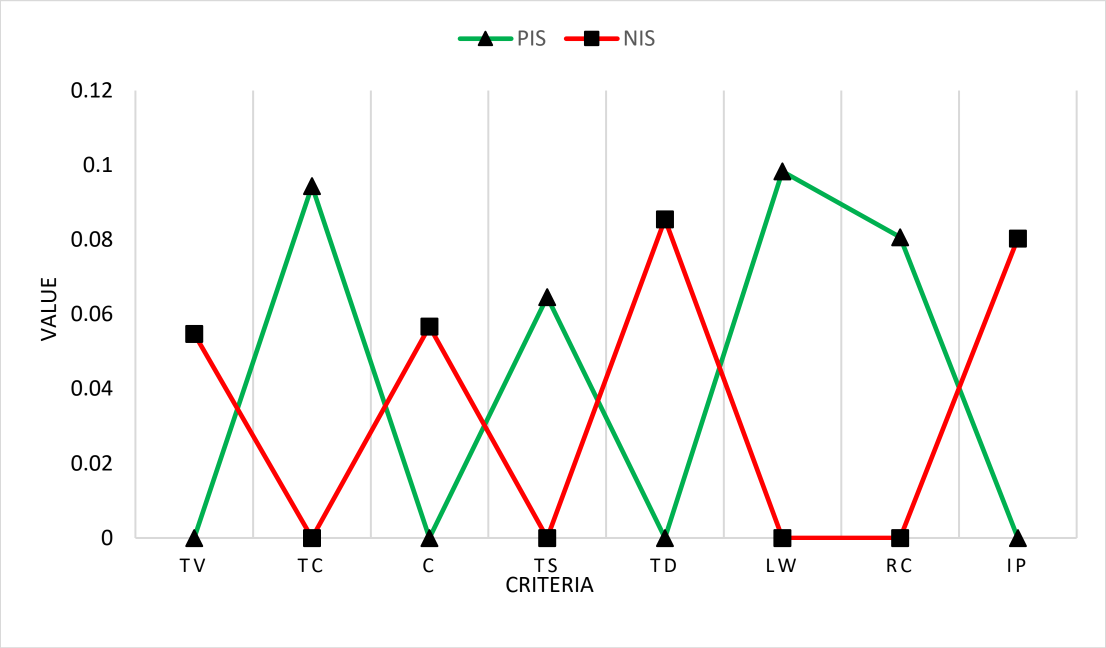

Figure 2-8: PIS and NIS Planes

As shown in figure 8 above, the values for cost criteria TV, C, TD, and IP are all 0 for PIS plane. This is due to the fact that, in contrast to the NIS plane, the PIS plane maintains the highest value of benefit criteria and the lowest value of cost criteria.

2.4.5.1 Route Ranking Using Objective Criteria Weights

The EWM criteria weights obtained were used to generate the routes for emergency evacuation of PWDs through TOPSIS application. Figure 2-9 shows the relative closeness, route ranking and the map for the three best evacuation routes, obtained by using only EWM weights.

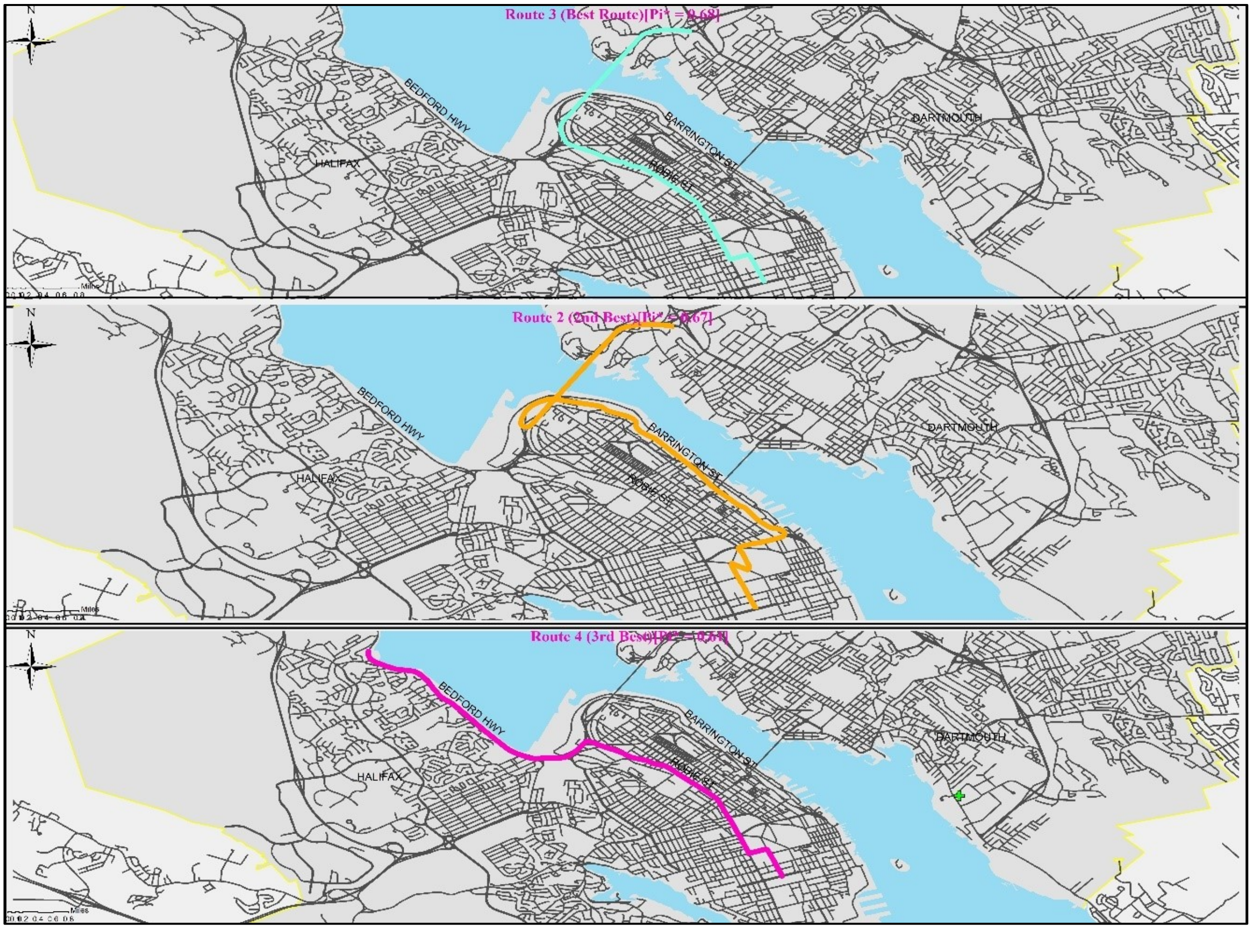

Figure 2-9: Maps of Best Emergency Evacuation Routes Produced using Objective Weights

Based on the P_i^* values, Routes 3, 2, and 4 respectively are the most promising routes for the emergency evacuation of PWDs. The three optimal routes have wider lanes, less traffic volume on weekdays, low incident probability and high capacities which allows efficient and safe evacuation of PWDs.

2.4.5.2 Route Ranking Using Optimized Criteria Weights

In this section, the optimized set of criteria weights obtained by the cloud model optimization process were used to generate the optimal routes for emergency evacuation of PMA through TOPSIS application. Figure 2-10 shows the relative closeness, route ranking and map for the three optimal evacuation routes, using optimized criteria weights.

Figure 2-10: Maps of Three Optimal Emergency Evacuation Routes

Based on the P_i^* values, Routes 2, 3, and 4 respectively are the most promising routes for the emergency evacuation of PMA. The three optimal routes have wider lanes, less traffic volume on weekdays, low incident probability and high capacities which allows efficient and safe evacuation of PMA. Using optimized weights as compared to objective weights produces route 2 as the best evacuation route. While using objective weights for route ranking produces route 3 as the best route as shown in figure 2-9. Emergency evacuation managers gave higher subjective weights to the criteria LW, RC, IP, and TS. Route 2 has the lowest incident probability, wider lanes as compared to all other 5 routes, best road condition, and highest design speed. Hence, using optimized weights for TOPSIS application route ranking produces route 2 as the best route followed by routes 3 and 4.

2.4.6 Comparative Analysis of Route Ranking

This study develops a route selection model for emergency evacuation planning of PMA, considering traffic and road condition related criteria using MCA. Initial objective criteria weights are calculated using EWM, then subjective weights were assigned to criteria by emergency evacuation managers. Next, the cloud model optimization process is utilized to combine the objective and subjective weights and generate an optimal set of criteria weights for route ranking. Table 2-7 shows the criteria values of the top three routes ranked by the TOPSIS application. Also, objective weights and optimized weights used in the TOPSIS route ranking process.

Table 2-7: Criteria Values of Best Routes Produced using Different Types of Weights

Routes	Rank	TV	TC	C	TS	TD	LW	RC	IP
		(MTV)	(v/h)	(V/C)	(km/h)	(km)	(m)	(Quan)	(%)
R2	**1**	**80937**	**1980**	**0.92**	**80**	**10.0807**	**3.8**	**4**	**30**
R3	**2**	**52649**	**1980**	**0.6**	**80**	**7.97563**	**3.7**	**3.5**	**80**
R4	**3**	**61694**	**2475**	**0.71**	**80**	**8.61085**	**3.4**	**3.5**	**80**

Optimized Weights (%)		**9.6**	**13.3**	**10**	**12.9**	**13.2**	**14**	**13.7**	**13.2**
Routes	Rank	TV	TC	C	TS	TD	LW	RC	IP
		(MTV)	(v/h)	(V/C)	(km/h)	(km)	(m)	(Quan)	(%)
R2	**2**	**80937**	**1980**	**0.92**	**80**	**10.0807**	**3.8**	**4**	**30**
R3	**1**	**52649**	**1980**	**0.6**	**80**	**7.97563**	**3.7**	**3.5**	**80**
R4	**3**	**61694**	**2475**	**0.71**	**80**	**8.61085**	**3.4**	**3.5**	**80**
Objective Weights (%)		**8.7**	**15.4**	**8.8**	**13.2**	**8.6**	**17.1**	**13.9**	**14.3**

Figure 2-11 demonstrates the comparison of optimal route ranking using TOPSIS application, considering objective criteria weights and optimized criteria weights. The table 2-7 above presents the optimized weights obtained through the combination of subjective and objective weights process, alongside the objective weights derived using the EWM.

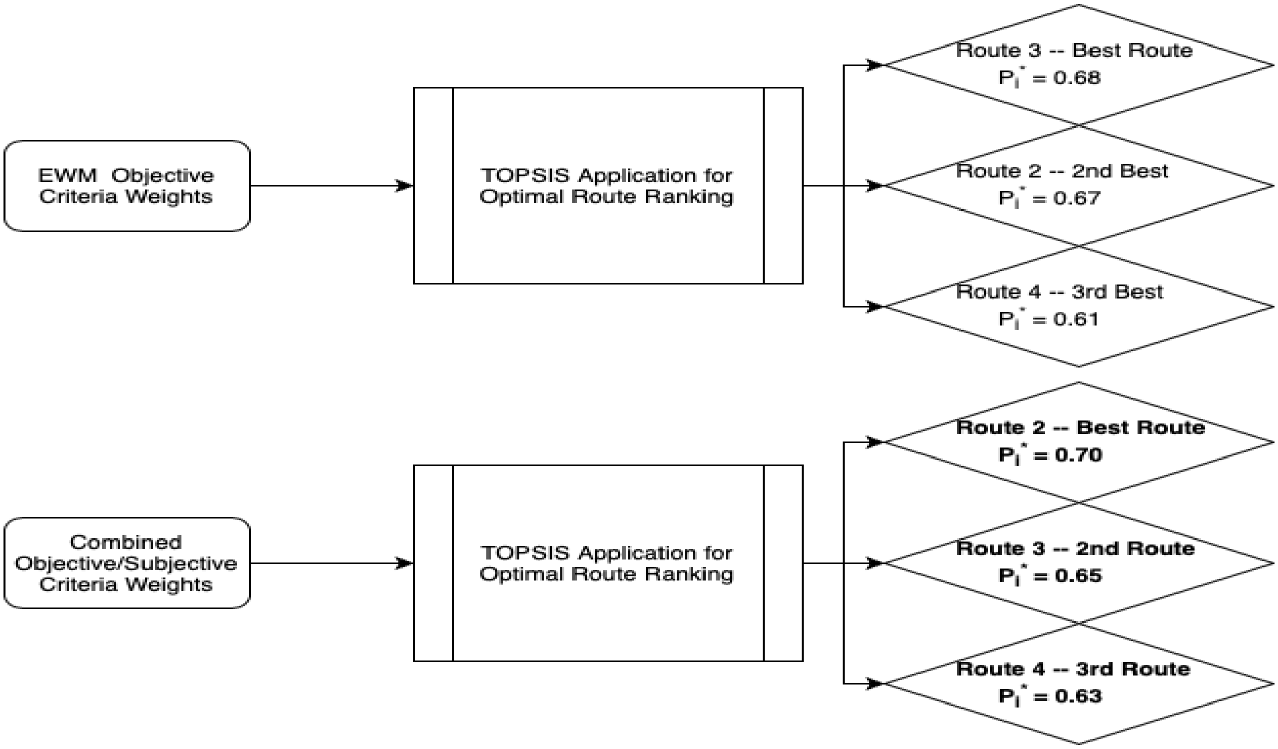

Figure 2-11: Route Ranking for Different Criteria Weights

Initially, TOPSIS application considers objective weights to produce the route ranking. Next, the TOPSIS application produces optimal route ranking by utilizing combined objective/subjective weights. As illustrated in figure 11, using objective weights the route ranking is as follows: $R_3 > R_2 > R_4$. Using objective weights to produce the optimal route ranking suggests route 3 is the best evacuation route to evacuate the PMA from Halifax Peninsula, with the P_i^* score of 0.68. Next, using an optimized set of criteria weights in the TOPSIS application produces the route ranking as follows: $R_2 > R_3 > R_4$, suggesting route 2 is the optimal evacuation route to evacuate PMA with the with the P_i^* score of 0.70. Figure 2-7 demonstrates that emergency evacuation managers firmly disagreed with the objective weights of the TD, TC, and LW criteria. The emergency evacuation managers gave TD top priority. TD has an optimal weight of 13.2%, which is greater than its objective weight of 8.6%. Similarly, both TC and LW have optimized weights that are less than the objective weight. Figure 2-7 also shows that the highest optimal criteria weights are assigned to LW, RC, TC, and IP, in that order. The best optimal route 2 with optimized weights has the greatest lane width of any route, the finest road conditions of any route, the greatest traffic capacity, and the lowest incident probability. Making it an optimal evacuation route for PMA emergency evacuation. Furthermore, the highest objective criteria weights are assigned to LW, TC, IP, and RC. Using objective weights, the best possible evacuation route 3 has wider lanes and the same traffic capacity as route 2. The main distinction is that objective criteria weights place a lower priority on incident probability and road condition criteria than optimized criteria weights. As a result, despite having a high incident probability and average road conditions, it is regarded as the best route. The explanation for this is that route 3 has a shorter overall distance, a lower congestion ratio, and a faster travel speed. Therefore, the idea of real-world subjective relevance combined with objective weights is the sole basis for the variation in route rankings. When determining the optimal evacuation routes, the concept of combining objective and subjective weights entails a perspective from the reality of the emergency evacuation process.

2.4.7 Comprehensive Analysis of the Optimal Route Characterises

TOPSIS application ranked three optimal evacuation routes using the optimized set of criteria weights, the optimal route ranking is as follows: $R_2 > R_3 > R_4$. Table 2-8 below shows the criteria values and optimal weights for each optimal route.

Table 2-8: Optimal Route Criteria Values and Weights

Routes	TV	TC	C	TS	TD	LW	RC	IP
	(MTV)	(v/h)	(V/C)	(km/h)	(km)	(m)	(Quan)	(%)
R2	**80937**	**1980**	**0.92**	**80**	**10.0807**	**3.8**	**4**	**30**
R3	**52649**	**1980**	**0.6**	**80**	**7.97563**	**3.7**	**3.5**	**80**
R4	**61694**	**2475**	**0.71**	**80**	**8.61085**	**3.4**	**3.5**	**80**
Optimized Weights (%)	**9.6**	**13.3**	**10**	**12.9**	**13.2**	**14**	**13.7**	**13.2**

	TV	TC	C	TS	TD	LW	RC	IP
Objective Weights (%)	**8.7**	**15.4**	**8.8**	**13.2**	**8.6**	**17.1**	**13.9**	**14.3**

According to the emergency evacuation managers, the best evacuation route 2 contains all of the finest criteria to be the best emergency evacuation route, as seen in the table above. The route has a 30% incident probability, making it the safest evacuation route for PMA. It has the best road conditions and the highest traffic capacity of 1980 v/h, indicating that it can manage the maximum volume of traffic. The route has the widest lane width of all the routes at 3.8 m, with a high travel speed of 80 km/h, implying that the driver may actually proceed at the route's maximum design speed without being concerned about the restricted lane width. Moving on to the second best route 3, while having a high incident probability, the route has other excellent characteristics that make it an excellent evacuation route. For example, this particular route has an average lane width of 3.7m, the lowest congestion ratio of all routes at 0.6 v/c, strong traffic capacity, and a high travel speed of 80 km/h. Route 3 provides emergency vehicle drivers with a less congested route and a shorter overall distance in order to get out of the danger zone. Finally, route 4 has the maximum traffic capacity of all the routes at 2475 v/h, indicating that it can handle the most traffic flow. The route also boasts excellent road conditions, a low congestion ratio of 0.71 v/c, and a high travel speed at 80 km/h. Overall, it is a decent emergency evacuation route.

2.5 Conclusion

This study develops a novel hybrid approach to the route selection model to generate the best emergency evacuation routes for PMA, considering traffic and road condition related criteria using MCA. Furthermore, the study optimizes the objective and subjective weights assigned to criteria, and produces an optimized set of criteria weights for optimal route ranking for emergency evacuation of PMA. Initial emergency evacuation route screening is performed considering a collision hotspot analysis of the Halifax peninsula. Based on collision probability, six routes were chosen for the optimal route selection analysis. The study decides weights for traffic and road condition related factors using multiple processes. Firstly, initial objective weight calculations were completed to assign objective weights to criteria depending on information entropy. Next, subjective weights were assigned to criteria by practicing transportation planners and emergency evacuation managers. Finally, an optimized set of criteria weights was produced by the cloud optimization process of combining objective and subjective weights. The results reveal that route 2 is the best route for the emergency evacuation of PMA, and the route selection model gives the following three best routes for emergency evacuation of PMA, from the Halifax Peninsula: $R_2 > R_3 > R_4$. This study's methodology can be implemented in many geographical areas, and the route selection optimization model can be changed to integrate newly identified criteria for emergency evacuation route selection for PMA. This study considers emergency vehicles to evacuate PMA, as most PMA will require assistance to evacuate. However, in extreme events use of other vehicles may be necessary and further studies can analyze the use of general vehicles. Moreover, Initial emergency evacuation route screening process only considers collision hotspot analysis to select the initial routes with minimum incident probability. However, the impact of disaster itself can make traffic routes inaccessible, due to flooding or excessive fire in some neighborhoods. Future studies can consider impacts of disasters when performing initial evacuation route screening. Furthermore, the authors suggest that the route selection model can further improvise by adding destination choice for PMA, including capacity constraints.

This study has some limitations. The study's reliance on collision information from the past is one of its limitations. Due to the lack of observed collision data specifically pertaining to the evacuation procedure during disasters, the study had to rely on historical records to analyze collision patterns. However, this approach may not completely capture the unique dynamics and difficulties that arise in a real-world evacuation scenario. Future studies would significantly benefit from incorporating real-time collision observations during disasters to address this limitation. By collecting and analyzing collision data specific to evacuation situations, researchers can develop more accurate models and strategies to enhance the safety and efficacy of evacuation processes. For TOPSIS computation, for instance, the authors are confident that the approach taken in this study is suitable for the problem at hand. In certain situations, such as when it is problematic to get the solution plane, it may be essential to change the solution plane either positive or negative, to fulfill the demands of factors and applications in practice. Also, the data standardization approaches used in the study are the ones that gave prominent results for the data used in this study. Other standardization methods can produce different results, affecting the outcome of the study.

Nevertheless, in the urgent need for emergency evacuation route planning specifically for PMA, this study fills a gap by developing an emergency evacuation route selection model for PMA considering traffic and road condition related criteria. The findings of this research will enable emergency evacuation management experts in the formulation of policies and the management of challenges and dangers linked with PMA evacuation by providing knowledge on how to mitigate them. The model can be used to plan pre-disaster evacuation of PMA using normal weekday traffic volume conditions, or it can be used to plan evacuation during the disaster using maximum traffic volume conditions. This research will help emergency evacuation managers and disaster management departments to make protocols and guidelines to achieve timely planning of evacuation of PMA.

Chapter 3

Emergency Evacuation Microsimulation Modelling[1] [2]

3.1 Introduction

Natural and man-made disasters are a constant danger, and different regions on Earth are growing increasingly susceptible to catastrophic weather events. Natural disasters have struck the planet on regular intervals over the last century. Such natural disasters are frequently large-scale and overpowering events that cause permanent and unmanageable destruction. There were 297 natural disasters in 2016, an increase of about 117% compared to the yearly global average from 1916 to 2015, as reported by the Centre for Research on the Epidemiology of Disasters (CRED) *(CRED, 2022)*. Furthermore, natural disasters killed over 377 million people and cost the global economy $93 billion in 2016 *(CRED, 2022)*. As the majority of fatalities were seniors aged 60 and up, Hurricane Katrina focused global attention on the significance of evacuation strategies for vulnerable groups *(Renne, 2018)*. Despite the fact that the planning and regulation of evacuation strategies for vulnerable populations are still in the works, *Renne (2018)* argues that there are several compelling reasons why society cannot afford to ignore evacuation preparation for these individuals. Rising sea levels, climate change, and the possibility of flooding are the foremost and most severe concerns right now *(Renne, 2018)*. According to recent forecast, sea levels might increase by 0.8 to 1.05 meters by 2100, with the majority of scientists

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[1] This chapter is adapted from:

Memon, A.W., and Habib, M. A. (2023). Optimizing Evacuation Planning for Persons Needing Mobility Assistance: A Microsimulation-based Modelling Study with Dual Destination Scenarios. *Journal of Transport Geography. (Under Review)*

[2] Memon, A. W., and Habib, M. A. (2023). "Microsimulation-based Evacuation Modelling for Persons Needing Mobility Assistance", Peer-reviewed proceedings of World Conference on Transport Research (WCTR), Montreal, Canada, July 17 – 21, 2023

forecasting a 1-meter rise *(BAMBER and ASPINALL, 2013; Rignot et al., 2011)*. Natural disasters provide a larger risk now than in the past due to climate change. Climate change is expected to cause inundation, including storm-induced coastal floods, frequent wildfires, and more severe weather events *(Renne, 2018)*. Evacuation preparations must account for the vulnerable due to shifting demographics and an aging population. As the population ages, an increasing proportion of people will be unable to drive or may require specific medical equipment for travel; consequently, failing to consider this information could lead to serious issues during an emergency evacuation *(Renne, 2018)*. Families with disabled individuals are less likely to evacuate during an emergency, and not evacuating is primarily attributed to a lack of resources and assistance *(Willigen et al., 2002)*. *Brodie et al. (2006)* corroborate the patterns observed in previous disasters and shed light on the circumstances confronting Katrina's victims. Their research indicates that those who remained in New Orleans during the hurricane either lacked access to a vehicle, misjudged the severity of the storm, or was unable to flee due to an illness or disability they or a family member had. *Benevolenza and DeRigne (2019)* found in their study the need for separate and specialized emergency evacuation planning for a variety of vulnerable populations, including those with disabilities. As these populations have specific evacuation requirements, they must be given *priority (Benevolenza and DeRigne, 2019)*. Disabilities like limitations in pain tolerance, mobility, and cognition are often the most prevalent in Canada. In 2017, around 6.2 million Canadians aged 15 and older, or almost one-fifth of the population, had a disability. At ages 15 to 24, the prevalence of handicaps was 13%, whereas it was 47% for those aged 75 and beyond. Disability was more prevalent among women (24%) than among men (20%) *(Morris and Brisebois, 2018)*. The growing number of Canadians with disabilities has brought mobility and cognition challenges to the forefront. Thus, evacuation planning for the disabled population require immediate study and development.

Most studies to date have focused on evacuation research for the general population, with few focusing on Persons with Disabilities (PWDs), with insufficient emphasis paid to emergency evacuation preparation for Persons Needing Mobility Assistance (PMA). PWDs are disabled individuals who can self-evacuate if emergency evacuation management provides instructions. PMA, on the other hand, refers to the disabled population that requires human or other vital assistance to escape. During a disaster, a visually impaired person will require human or other physical assistance to evacuate. In this study, only emergency vehicles (EMVs) are utilized to evacuate PMA, as only EMVs have personnel available to assist PMA during evacuation. Studies for PWDs emphasize on localized, small-scale measures, such as building or small facility evacuation. *Koo et al. (2013)* Provided evacuation strategies for PWDs in high-rise buildings, stressing the superior performance of the lift evacuation method considering evacuation time, ratio of move frequency, and rate of flow at stair sections. The analysis, however, did not account for PMA evacuation, making it difficult to organize and carry out an efficient evacuation *(Koo et al., 2013)*. Agent-based modeling (ABM) is employed in a separate study to evaluate how well airports would evacuate passengers with disabilities if a bomb was located in the terminal *(Manley et al., 2011)*. The emergency evacuation simulation presented by the ABM did not consider evacuation needs for PMA. *Noh et al. (2016)* propose a partially devoted evacuation method that dedicates one path to a fast-moving group of persons without disabilities and another to the remaining PWDs to reduce congestion. This strategy succeeds by determining the number of able-bodied people who use each level and path, but the issue remains that PWDs can evacuate by themselves and PMA will require assistance to evacuate the building *(Noh et al., 2016)*. On other occasions, researchers have discovered unique evacuation issues for hospitals and senior care centers. *Hashemi (2018)* emphasized the major findings from the literature on PWDs emergency evacuation, as well as the flaws and research gaps that must be addressed in the future. Due to a lack of evacuation planning for PMA, there is an urgent necessity, knowledge, and practical application gap when it comes to mass evacuations of PMA on a city or regional scale. Closing this gap includes designating optimal emergency evacuation routes considering traffic volume and road condition related criteria to evacuate PMA. This study utilizes designated emergency evacuation routes within the evacuation microsimulation model. Microsimulation of traffic plays a crucial role in advancing our understanding of how to improve the evacuation of disabled populations by taking into account crucial factors such as time sensitivity, uncertainty, traffic congestion, and evolving road conflicts. Utilizing traffic microsimulation allows for a comprehensive examination of the dynamics and complexities of traffic behavior during evacuation scenarios, thereby providing valuable insights for enhancing the evacuation procedure.

Microsimulation models allow the examination of various strategies and interventions to reduce evacuation time, mitigate uncertainties, manage traffic congestion, and resolve emerging road network conflicts by including realistic representations of individual vehicle movements, interactions, and decision-making. Therefore, using traffic microsimulation allows for more rational decision-making and the optimization of evacuation plans that are adapted to the needs of the disabled population. In the previous chapter, the authors presented the top three ranked routes as optimal routes. However, in this chapter, they extend the evaluation by considering the top four ranked routes. The purpose is to obtain a more comprehensive understanding of all potential evacuation routes that can be utilized in emergency situations. Additionally, since Halifax has limited entry and exit points, increasing the number of evaluated routes enhances the likelihood of identifying sufficient exit points, thus enhancing the overall evacuation process's effectiveness. Thus, this research designates four optimal evacuation routes of Halifax Peninsula, Nova Scotia for evacuation of PMA, obtained by the route selection model developed by *Memon and Habib (2023)*. This study incorporates those routes within the microsimulation model for traffic evacuation developed by *Alam et al. (2018)*, to determine Average Evacuation Time (AET) for a single emergency vehicle (EMV) to exit the peninsula. The traffic evacuation microsimulation model only uses EMVs to evacuate PMA from hospitals and senior care centers of the Halifax Peninsula using designated evacuation routes. For the network-level analysis, a fleet of 200 EMVs was utilized, the combined resources of Nova Scotia Emergency Health Services (139 vehicles) and the Halifax Regional Municipality (HRM), which has 41 access-a-bus vehicles and 20 spare EMVs *(Halifax Transit, 2021; EHS, 2012)*. The utilization of 200 emergency vehicles is attributed to the limited availability of emergency vehicles within the Nova Scotia Health Service and HRM combined.

The technical objectives of this study are: (1) Using four designated evacuation routes obtained by the route selection model to evacuate PMA, and (2) developing three different traffic volume/condition related cases within the microsimulation model for traffic evacuation to test and evaluate the AET under two destination-based scenarios. To achieve this, the study selects four optimal routes within the Halifax Peninsula produced by the route selection model as designated evacuation routes. Next, the routes are incorporated within the microsimulation model for traffic evacuation to evaluate AET for a single EMV to exit the peninsula safely. Further, under two destination-based scenarios: (1) Out of Danger Zone (ODZ), (2) To the Shelter Location (TSL), the microsimulation model will implement three cases: (1) AET of an EMV considering Annual Average Weekday Traffic (AAWT), (2) AET of an EMV considering instantaneous mass evacuation traffic volume condition, and (3) AET of an EMV under a policy direction of the dedicated lane and green signal time for EMVs evacuating PMA. The results demonstrate that designating optimal evacuation routes obtained by the route selection model provide safe and efficient evacuation of PMA. The dedicated lane and green signal time policy direction is the fastest way to evacuate PMA from the Halifax Peninsula.

3.2 Literature Review

A growing body of academic research has argued for the greater and more pressing necessity for realistic and comprehensive evacuation planning and modeling of masses in recent decades *(Wolshon et al., 2005)*. After 2005's Hurricane Katrina, disaster management experts have consistently expressed grave concerns regarding the inadequacy of PWDs and PMA evacuation plans. There is a scarcity of studies that relates mass evacuations of PWDs to larger networks and modeling frameworks, despite the expanding volume of literature. Some emergency evacuation planning research is utilizing advanced optimization methods, adaptive modeling and simulation methods to assist PWDs evacuation planning. *Ebrahimnejad et al. (2021)* developed an optimization model for the evacuation of PWDs. This research examined a mixed integer linear programming model. The study's purpose was to determine the optimum approach to assign different categories of PWDs to different types of vehicles, as well as to route cars to pick up PWDs during evacuations *(Ebrahimnejad et al., 2021)*. In a separate study, *Kaisar and Portal (2012)* employed a linear programming optimization approach to design a public transportation routing scenario that best supports PWDs in the District of Columbia's downtown core. The study's major purpose was to recommend optimal sites for evacuation bus stops and to build a realistic microscopic transportation network simulation *model (Kaisar and Portal, 2012)*. According to *Kaisar and Portal (2012)*, the scenario with 60 evacuation bus stop sites would be optimal for planning purposes. This scenario had the shortest delay, transit, and stop times due to the best geographic distribution of evacuation bus stations. Furthermore, *Manley and Kim (2012)* presented an agent-based microscopic simulation model for creating and testing a public Decision support system (DSS), as well as insights and discoveries that may be used by all private firms to design an emergency evacuation strategy to assure company continuity. In the event of an emergency, the aforementioned concept is specifically built to securely evacuate PWDs *(Manley and Kim, 2012)*. The Exitus system, created by *Manley and Kim (2012)*, replicates heterogeneous populations more precisely since it takes into account a wider variety of mental and physical characteristics exhibited by PWDs. The aforementioned study aided in the evacuation planning for persons with disabilities by employing optimized programming models and simulation models to assign PWDs to evacuation vehicles, route vehicles to PWDs pick-up locations, and locate suitable evacuation bus stations. There is a gap in evacuation planning for persons needing mobility assistance, described as PMA in this study. For instance, PMA will need assistance reaching evacuation pick-up locations. In addition, certain PMA will necessitate the use of EMVs and personnel to evacuate in a secure manner. Therefore, evacuation models must include pick-up locations that are optimally suited for PMA, such as emergency centers or hospitals. Also, consider employing EMVs for certain PMA. Methodologically, the following section explains how microscopic simulation modeling techniques have been used to address a number of evacuation planning problems for general population. In one study using an existing microscopic simulation model to improve evacuation techniques, *Jha and Pashaie (2004)* analyzed how MITSIMLab was utilized to construct a network simulation model and how that model was used for emergency evacuation preparation. It was demonstrated that extensive modeling of traffic operations, including signal control, was required for effective evacuation forecasts. Many criteria are used to evaluate the effectiveness of simulated evacuations, including time-dependent evacuation progression, the population at risk, and bottleneck areas *(Jha and Pashaie, 2004)*. In a subsequent study, *Zou et al. (2005)* created a simulation-based disaster response evacuation system. The integration of optimization and simulation in the proposed model enables prospective Users to update the optimum plan for both strategizing and dynamic operations. When correctly connected with network traffic detectors, the suggested system can be used to track how traffic conditions change throughout an evacuation and evaluate the efficacy of diverse tactics for addressing unforeseen obstacles *(Zou et al., 2005)*. Moreover, *Franzese (2002)* sophisticated simulation modeling system called OREMS, that can be used to plan and forecast evacuations for user-defined spatial boundaries, regardless of the weather, time of day, or other external factors. Evacuation response rates, alternate routes, and final destinations are all customizable in this system. The time needed for evacuation or clearing, as well as traffic operational aspects like bottlenecks in traffic, can be calculated in each scenario *(Franzese, 2002)*. For the purposes of a hurricane evacuation, *Fu and Wilmot (2004)* developed a sequential binary logit model, that is used to predict whether or not residents of a certain household will evacuate based on demographic information, hurricane conditions, and government response. In the wake of Hurricane Andrew, researchers in southwest Louisiana gathered data to use in estimating a model that predicted dynamic storm evacuation travel demand estimates *(Fu and Wilmot, 2004)*. Next, *Chen and Zhan (2008)* using agent-based simulation investigated the cumulative evacuation duration of the simultaneous and stage evacuation strategies. Staged evacuation splits the affected region into zones and organizes residents in separate zones to leave sequentially, while simultaneous evacuation orders all affected residents to evacuate simultaneously *(Chen and Zhan, 2008)*. Several simulations suggest that no evacuation method is ideal across a variety of road network designs. Road network structure and population density affect strategy performance *(Chen and Zhan 2008)*. The aforementioned studies conducted assessments on traffic operations, types of disasters, demographic factors, and a range of evacuation strategies through the utilization of simulation methodologies. These endeavors were undertaken with the aim of enhancing preparedness for community at large. In preparing for PMA evacuation, however, there is a gap because evacuation through EMVs requires consideration of shelter sites, route planning considering road conditions/traffic-related features, and human personnel for evacuation assistance. Furthermore, *Dulebenets et al. (2020)* present a ground-breaking multidimensional emergency evacuation planning optimization model for reducing overall evacuation duration, mental demand, physical demand, temporal demand, effort, and aggravation for people fleeing a specific metropolitan region in case of a catastrophic event. Unlike most prior emergency evacuation and planning studies, *Dulebenets et al. (2020)* created an optimization model that factors in multiple drivers, escape routes, and existing traffic conditions. To shorten the time it takes for people to evacuate a dangerous area, *Dulebenets et al. (2019)* created a mixed-integer programming technique. This study's objective was to develop an efficiency model and corresponding algorithmic approaches to guide individuals affected by a disaster toward secure locations and efficient escape routes. *Dulebenets et al. (2019)* determined that for large-scale problem settings, heuristic approaches outperformed accurate optimization algorithms. Driving simulators were utilized in a few evacuation planning studies. For instance, in order to quantify people's reported driving difficulties during an evacuation, *Abioye et al. (2020)* employed a driving simulation platform to recreate real-world emergency evacuation scenarios. Statistics models were developed to evaluate the cognitive stressor demands incurred by displaced individuals as a result of the emergency evacuation based data from the driving simulation platform. *Abioye et al. (2020)* found that drivers with more experience logged significantly more hours of mental, physical, temporal, effort, and frustration behind the wheel than those with less experience. Experienced drivers logged more hours of physical, temporal, effort, and frustration behind the wheel because their familiarity with driving tasks and road conditions may lead to prolonged driving sessions, resulting in increased physical strain, time spent on the road, mental effort in handling complex situations, and occasional frustration with traffic challenges. The majority of the studies mentioned above use autos for simulation modeling, with only a handful focusing on bus-based evacuation. However, only PWDs who can use public transportation will benefit from bus-based evacuation planning. PMA, on the other hand, necessitates the use of specialized EMVs for evacuation. Moreover, the studies cited above also make the assumption that those without cars and mobile PWDs are supposed to meet at designated pick-up locations to be taken to shelter locations. Immobile PWDs, or PMA, will require special vehicles to transport them, primarily from hospitals and nursing homes. Furthermore, due to several problems such as traffic congestion and incidents, EMV operations in the network may not be as successful as anticipated. As a result, emergency evacuation route planning is needed for PMA, considering using pre-determined designated evacuation routes to perform safe and efficient evacuation of PMA. The novelty of this study is that it selects four designated evacuation routes and incorporates those routes into a microsimulation model for traffic evacuation to test and evaluate AET, using only EMVs to evacuate PMA hospitals and senior care centers. The traffic evacuation microsimulation model implements three different traffic volume/condition related cases under two destination-based scenarios for the evaluation of AET of a single EMV to exit the Halifax Peninsula safely.

3.3 Methodology

The study's goal is to develop a strategy for evacuating PMA in a secure manner using only EMVs from the Emergency Health Authorities of Nova Scotia. PMA from the major hospitals and senior care facilities in the Halifax peninsula are being evacuated and taken to either Dartmouth General Hospital or the Cobequid Emergency Centre. Among the many parts that make up the modeling framework are those that determine four designated evacuation routes, add those routes to a traffic evacuation microsimulation model, and use that model to put AET through its paces in three different traffic volume/condition-based test cases, under two distinct destination-based scenarios. The first scenario is called the ODZ scenario, where AET to just exit the Halifax Peninsula is determined for an EMV, in order to estimate the time required to get PMA out of imminent danger. Figure 3-2 below indicates the ODZ boundary. The second scenario is named the TSL scenario, where AET of safely transporting PMA to shelter locations mentioned above is determined, for a comprehensive understanding of how long it will take to evacuate PMA to shelter locations. Figure 3-1 provides a high-level overview of the evaluation framework needed to determine the AET for a single EMV to safely transport PMA from hospitals and senior care centers along predetermined evacuation routes.

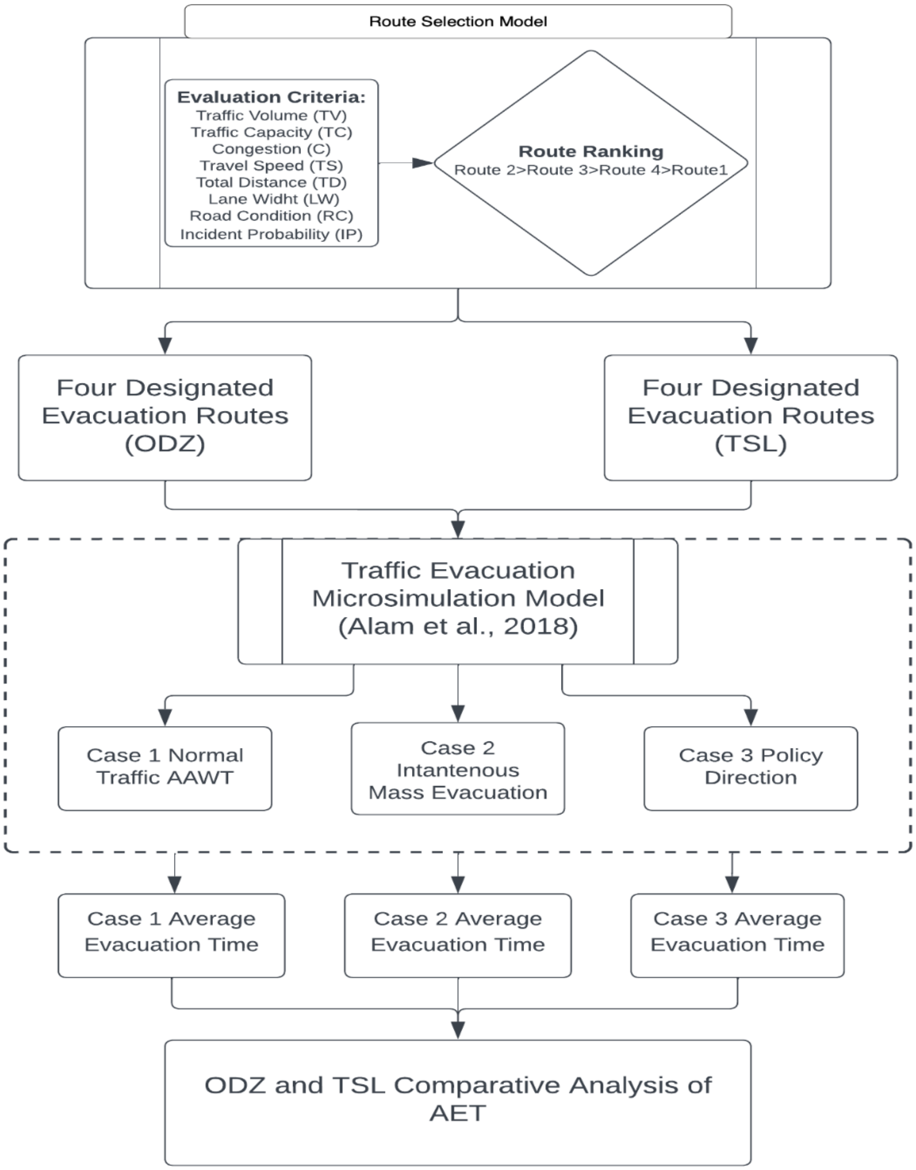

Figure 3-1: The Conceptual Framework for Modelling PMA Evacuation

In this research, a route selection model was used to (1) determine the designated evacuation routes. (2) incorporating designated evacuation routes within the framework of the traffic evacuation microsimulation model. (3) Creating three distinct traffic volume/condition cases in order to evaluate the AET performance of a single EMV under ODZ and TSL scenarios. (4) Performing comparative analysis of AET results for both destination-based scenarios to decide the fastest evacuation route to evacuate PMA safely, and concluding some of the important traffic operations/planning parameters affecting AET and route choice to evacuate PMA. As visualized in figure 3-2, this study considered the Halifax Peninsula as a potential emergency evacuation site for PMA.

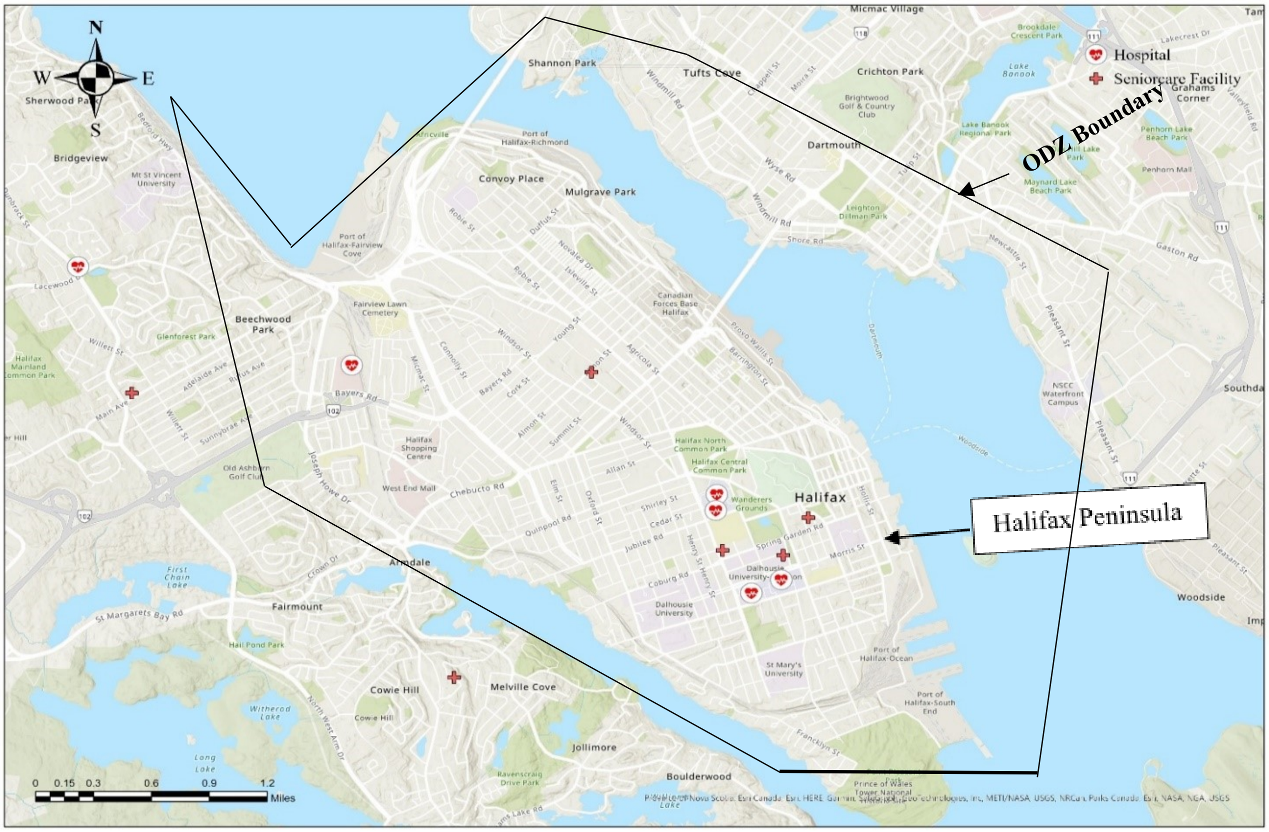

Figure 3-2: Study Area Map

3.3.1 Designated Evacuation Routes Selection

In this study designated evacuation routes are selected from the optimal routes obtained by the route selection model developed by *Memon and Habib (2023)*. The route selection model uses a multi-criteria analysis approach, taking into account eight distinct variables linked to traffic and road conditions, to choose the best possible evacuation routes. The following criteria were identified as the key contributing variables for evaluating emergency evacuation routes, based on both real emergency evacuation operations and the opinions of transportation planning professionals: (1) Traffic Volume

(TV); (2) Traffic Capacity (TC); (3) Congestion (C); (4) Travel Speed (TS); (5) Total Distance (TD); (6) Lane Width (LW); (7) Road Condition (RC); (8) Incident Probability (IP). The Criteria values for the six routes are shown in table 3-1. TD varies for two scenarios under consideration, ODZ and TSL.

Table 3-1: Alternative Route Criteria Values

Routes	**TV**	**TC**	**C**	**TS**	**TD (ODZ)**	**TD (TSL)**	**LW**	**RC**	**IP**
	(AAWT)	(v/h)	(V/C)	(km/h)	(km)	(km)	(m)	(Quan)	(%)
R1	16322	1485	0.82	80	5.20709	9	3.6	4	30
R2	18410	1980	0.92	80	10.0807	16.65	3.8	4	30
R3	11977	1980	0.6	80	7.97563	14.63	3.7	3.5	80
R4	14037	2475	0.71	80	8.61085	20.1	3.4	3.5	80
R5	10608	1000	0.54	60	6.02817	N/A	3.3	2.5	50
R6	10608	1000	0.54	60	6.93841	N/A	3.3	2.5	50

Each criterion in the route selection model is given a weight based on both objective and subjective evaluations, and this leads to a system of weights that is optimal for determining the best route for PMA emergency evacuation. Emergency evacuation routes are initially screened with a collision hotspot assessment of the Halifax Peninsula in mind. There are numerous methods for assigning weights to factors that relate to traffic and road conditions. To properly weigh the criterion, the process began by computing objective weights using the information entropy. Then, transportation planners and professionals in emergency evacuation operations assigned subjective weights to criteria. After balancing objective and subjective criterion weights, the cloud optimization technique produced the most effective set of weights. Using the route selection model, it was determined that Route 2 is the ideal option for evacuating PMA in the event of an emergency, followed by Routes 3, 4, and 1 from the Halifax Peninsula. Considering the two destination-based scenarios, ODZ routes are the routes generated by the route selection model, and TSL routes are generated by extending the above mentioned routes to two shelter locations. Table 1 shows the TD of routes for both scenarios.

3.3.2 Traffic Evacuation Modelling System

This study develops a traffic evacuation microsimulation model utilizing network provided by *Alam et al. (2018)* to investigate AET for a single EMV when addressing the evacuation of PMA under scenarios ODZ and TSL. Table 3-2 provides a high-level summary of the model.

Table 3-2: Elements, description, and Applications of Traffic Evacuation Microsimulation Model

Items	Description
Elements of Road Network	• Total 1784 links and connectors used • Total 41 Signalized intersections • Total 12 Stop signed intersections

	• Total 56 Traffic analysis zones • Total 200 EMVs used
Assignment process	• General Traffic Flow Follows Dynamic Traffic Assignment • Emergency Evacuation Vehicles Follow Static Traffic Assignment
Model Calibration and Validation	Three driving behavior parameter calibration: • Average standstill distance– 1.0 • Additive part of safety distance – 0.6 • Multiplicative part of safety distance – 0.7 Traffic volume-based validation: • R2= 0.82 and 0.84 respectively for two morning peak periods
Application	Three evacuation cases under two scenarios, ODZ and TSL: 1. Normal traffic AAWT. 2. Instantaneous mass evacuation traffic volume. 3. Policy direction of the dedicated lane and green signal time for EMVs.

3.3.2.1 Evacuation Transportation Network Elements

A microsimulation model for traffic evacuation is employed to replicate the realistic traffic dynamics observed in Halifax. The model encompasses a comprehensive representation of the intricate elements within the road network. The evacuation network is represented and simulated utilizing the PTV Vissim microsimulation software, renowned for its capability to accurately replicate real-world traffic dynamics. Figure 3-3 visually presents the map depicting the network's elements, providing a comprehensive and detailed overview of the network's structure.

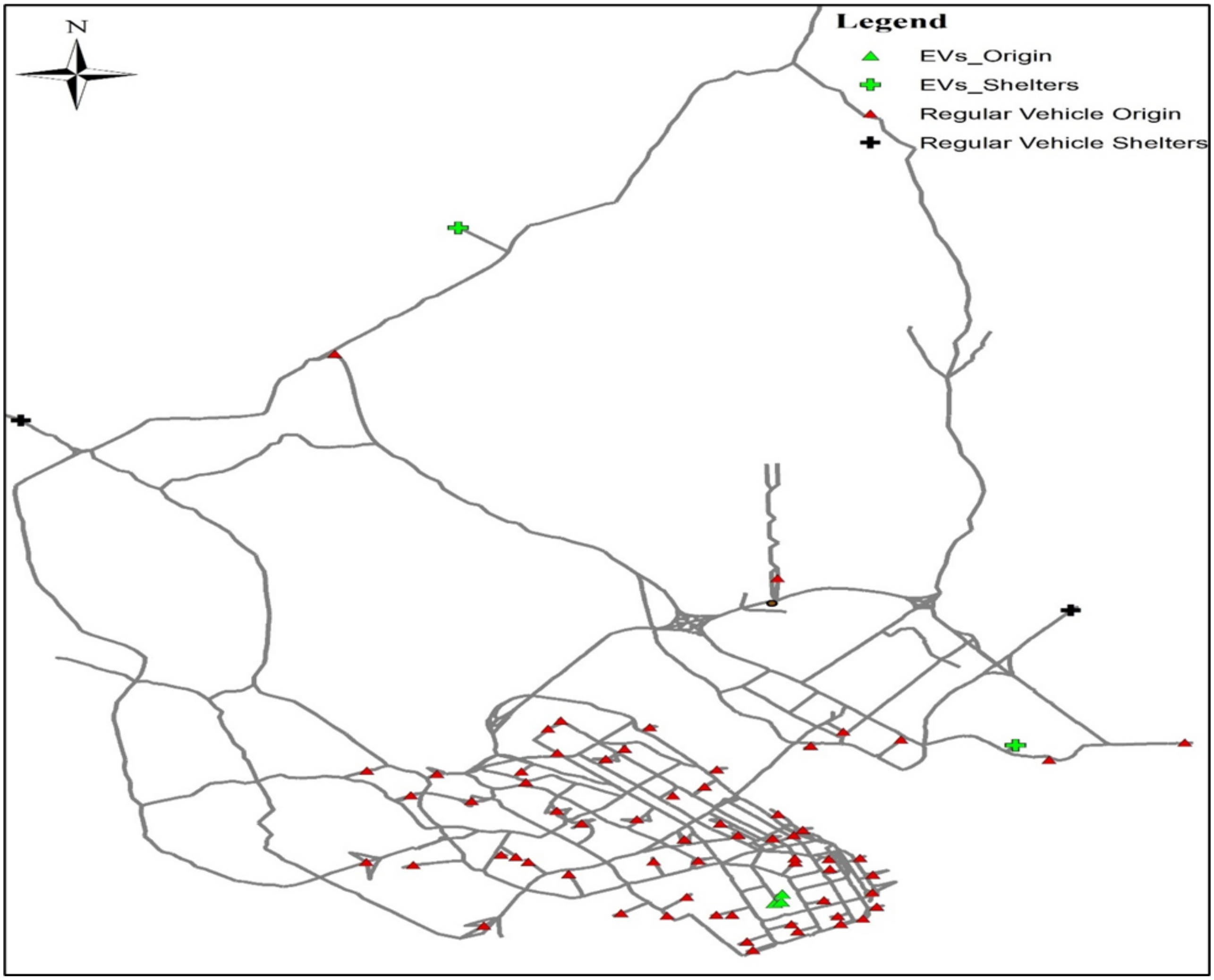

Figure 3-3: Map of the Evacuation Network Elements

Figure 3-3 presents a detailed depiction of the simulated evacuation network, which comprises a total of 1784 links and connectors. The network includes 41 signalized intersections and 12 stop signed intersections, strategically placed to regulate traffic flow. Additionally, the network is divided into 56 traffic analysis zones represented by parking lots of an origin and destination pair, facilitating a comprehensive understanding of traffic patterns and dynamics. Furthermore, the map highlights three designated EMV origin points within the network, serving as crucial starting locations for emergency response. For the purpose of evacuation network-level analysis, the simulation involves the utilization of 200 EMVs, enabling the assessment of evacuation strategies and emergency response effectiveness. The comprehensive representation of these elements within the evacuation network allows for detailed analysis and evaluation of traffic dynamics, congestion management, and the optimization of evacuation plans in emergency scenarios.

This study utilized Latin Hypercube Sampling (LHS) as a methodological approach for calibrating driving behavior parameters following *Alam et al. (2018) and (2019).* By generating a multitude of combinations of parameter values, LHS facilitated the exploration of diverse scenarios to identify the specific combination that most accurately resembled the observed driving behavior within the network. Through this rigorous calibration process, the researchers were able to align the driving behavior parameters with real-world data, enhancing the accuracy and realism of simulation model. The calibration of driving behavior parameters leads to a combination wherein the average standstill distance is determined to be 1.0, the additive component of the safety distance is measured at 0.6, and the multiplicative component of the safety distance is found to be 0.7. Next, the model's validation process involved comparing it to the actual traffic counts recorded at important intersections and various locations along the network's links. Subsequently, model validation was conducted by comparing the simulated results with observed traffic counts obtained from critical intersections and various locations along the network. The calibration process for route choice parameters was then carried out utilizing a link surcharge method. Two distinct datasets of traffic volume, acquired from the HRM, were employed in this calibration procedure. Following the validation process, the model's performance was assessed based on the goodness-of-fit measures, specifically the R^2 values. The obtained R^2 values for two morning peak periods were found to be 0.81 and 0.82, indicating a strong level of agreement between the simulated results and the observed traffic volumes.

3.3.2.2 Traffic Assignment Process and Model Modification

The microsimulation model for traffic evacuation employs a Dynamic Traffic Assignment (DTA) mechanism for regular traffic to accurately depict the propagation of traffic congestion and, consequently, the availability of alternative routes across all network segments. The algorithm periodically examines traffic conditions and modifies driver behavior accordingly, taking into consideration the dynamic nature of the transportation network. Within the DTA framework, there are various assets that play a crucial role, including the origin-destination matrix, simulation parameters like maximum iterations and convergence criteria with their associated tolerance, as well as additional cost components such as link surcharges. These assets collectively contribute to the effectiveness and accuracy of the DTA system. In early iterations of DTA, the distance was initially replaced with trip length to find the best time-efficient routes between two locations. Next, the routes are determined by repeatedly calculating and using the travel time efficiently from the iterations. The research applies equation (1) *(PTV, 2022)* during simulation to estimate trip time at the selected evaluation interval. Assume for the sake of argument that a car spends a significant amount of time on the edge. In that instance, the model will keep tracking that vehicle's travel time, factoring in the cumulative effects of congestion as more time passes throughout the network. It is standard practice to repeat the DTA procedure until convergence is achieved. One of the convergence requirements is the minimization of differences in traffic flow indicators such as traffic volume and edge travel time between iterations. In the context of transportation and traffic modeling, an "Edge" refers to a segment or link in the road network connecting two nodes or intersections. It represents a physical road or street where vehicles can travel. In the above given statement, "Edge Travel Time" refers to the time taken by a vehicle to traverse a specific edge or road segment from one end to the other. Subsequently, in the current model, the evacuation road network has been modified to integrate the designated evacuation routes identified through the route selection model. These designated routes, which are predefined, have been incorporated as static routes within the network. These routes originate from areas on the Halifax peninsula with the highest concentration of hospitals and senior care facilities, serving the purpose of evacuating the PMA. EMVs utilizing these pre-planned designated routes adhere to the static traffic assignment methodology, which involves an exact vehicle loading process into the evacuation road network.

$$T_i^{n,k} = \left(1 - \frac{1}{N+1}\right) \cdot T_i^{n-1,k} + \frac{1}{N+n} \cdot TO_i^{n,k} \tag{1}$$

Where:
n = Signifies iteration index
k = Signifies evaluation interval
i = Signifies edge index
N = User-defined value for number of iterations
$T_i^{n,k}$= Signifies travel time on $\boldsymbol{i}$,$\boldsymbol{k}$ and $\boldsymbol{n}$

$TO_i^{n,k}$= Signifies observed travel time on ***i***,***k*** and ***n***

3.3.2.3 Scenario Development and Identification of Shelter Locations

This study develops two destination-based scenarios for three traffic volume/condition cases. The first scenario is referred to as the ODZ scenario, in which the AET to just evacuate the Halifax Peninsula for an EMV is estimated in order to determine the duration of time needed to get PMA out of imminent danger. The second scenario, known as the TSL scenario, determines the AET of securely transporting PMA to the previously identified shelter locations in order to gain a comprehensive understanding of how long it will take to evacuate PMA to shelters.

The first case considers AAWT to perform emergency evacuation of PMA. The reason AAWT is considered as the traffic volume, as on weekdays traffic volume is higher than on weekends. Especially peak hour traffic volume is significantly higher on weekdays as compared to weekends. The event of evacuation after any disaster itself creates traffic congestion, as most people are using personal vehicles to evacuate. Using AAWT in the network provides a much better understanding of AET for a single EMV to exit the peninsula.

The second case considers people from the entire peninsula evacuating using various modes, including personal vehicles, public transport and EMVs. This scenario increases the traffic volume to the maximum in the network, creating more traffic congestion than usual. This scenario gives a more realistic idea of AET to exit the peninsula for an EMV. Since when a disaster happens or is about to happen, most people try to evacuate using any transportation mode conveniently available. Also, this scenario is used for this research for the reason that evacuation scenarios usually have significantly more traffic volume on road networks than under normal conditions.

The third case considers the simulation of emergency evacuation of PMA under a policy direction of dedicated lane and green signal time for EMVs. In this scenario, all EMVs evacuating PMA from hospitals and senior care centers of the Halifax Peninsula will have a dedicated lane, and green signal time on each of the designated four evacuation routes. This policy direction will result in a quick and efficient evacuation of PMA from the peninsula, but this case can create significant traffic congestion on the neighboring roads.

The selection of shelter locations is a crucial component of any evacuation plan. As a result of the physical grouping of shelter facilities by subdistrict, evacuees in a number of developing nations are able to locate refuge more quickly and efficiently. *Alam et al. (2021)* conducted a study for a comprehensive evaluation of shelter location selection. Their study employs multi-criteria analysis process to evaluate potential shelter locations based on a variety of factors. These factors are related to Environmental hazards, structural attributes of a shelter, proximity to emergency services, and accessibility. Because this study focuses on the evacuation of PMA from hospitals and senior care facilities, the shelters were chosen based on their size, accessibility, emergency medical services availability for PMA, and transportation considerations. The information about the chosen shelter places is provided in Table 3-3 below.

Table 3-3: Elements, description, and Location of Shelters

Shelter	Description	Location
Dartmouth General Hospital	• Hospital • High Accessibility • All Medical Emergency Services Provided for PMA	• Connected via Three of Designated Evacuation routes Route 1, 2 and 3
Cobequid Emergency Centre	• Emergency Centre/Hospital • High Accessibility • Most Medical Emergency Services Provided for PMA	• Connected via Route 4

The two shelter locations chosen, as shown in table 3-3, are adequately aligned with the criteria specified by the aforementioned study regarding shelter location selection for emergency evacuation. The two shelters chosen are easily accessible, offer all emergency medical services for PMA, and are on designated evacuation routes.

3.4 Results and Discussion

3.4.1 Designated Evacuation Routes Selection Results

In this study designated routes are selected from the optimal routes obtained by the route selection model developed by *Memon and Habib (2023)*. The four designated routes are considered safe and efficient to perform emergency evacuation for PMA. Figure 3-4 shows the map of four designated evacuation routes chosen to perform simulation-based tests and evaluations.

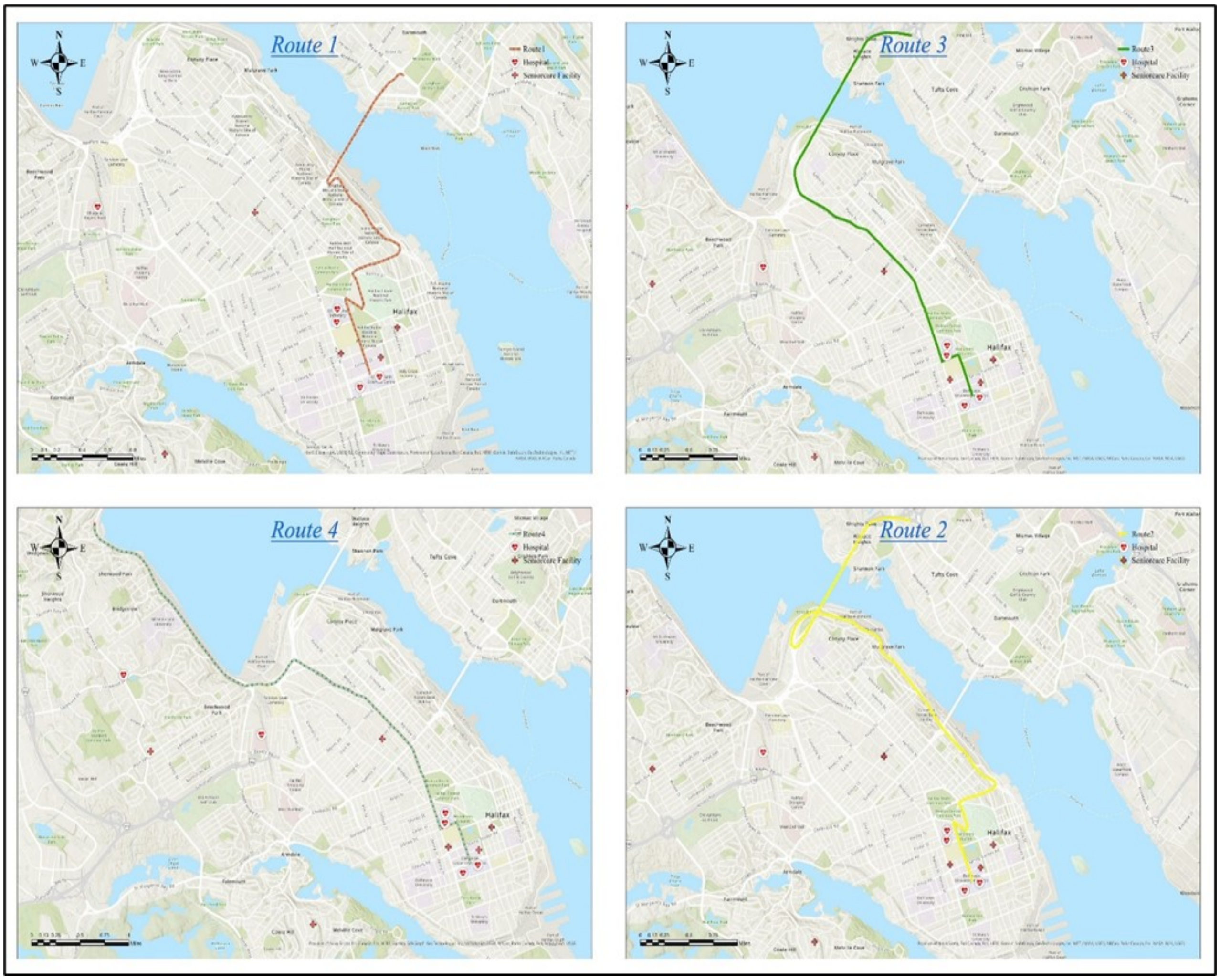

Figure 3-4: Four Designated Evacuation Routes ODZ Scenario

Figure 3-4 demonstrates that routes 1, 2, and 3 exit the Halifax Peninsula through the bridge, whereas route 4 exits via the Bedford highway. Analyzing table 1 reveals that routes 1 and 2 have the lowest probability of incidents among all routes, at 30%. Therefore, routes 1 and 2 are the safest evacuation routes based on the likelihood of collisions during the evacuation. Routes 3 and 4 have the best road conditions of 3.5 and a low traffic congestion rate. This study uses just EMVs to evacuate, considering all evacuation routes originate from the same location, near the majority of hospitals and senior care centers on the Halifax Peninsula. The selected routes have large traffic capacities, low incident probabilities, and wider lanes, allowing for the swift and simple evacuation of the PMA. Figure 4 displays the specified paths utilized in the ODZ scenario of the microsimulation model. Due the reason that the destination of these routes is just outside of the peninsula, following three exit points of the Halifax Peninsula.

To determine the AET of evacuating PMA safely to the shelter locations, the study extends designated evacuation routes to the Dartmouth General Hospital and the Cobequid Emergency Centre. Figure 3-5 shows the map of four designated evacuation routes leading to the selected shelters.

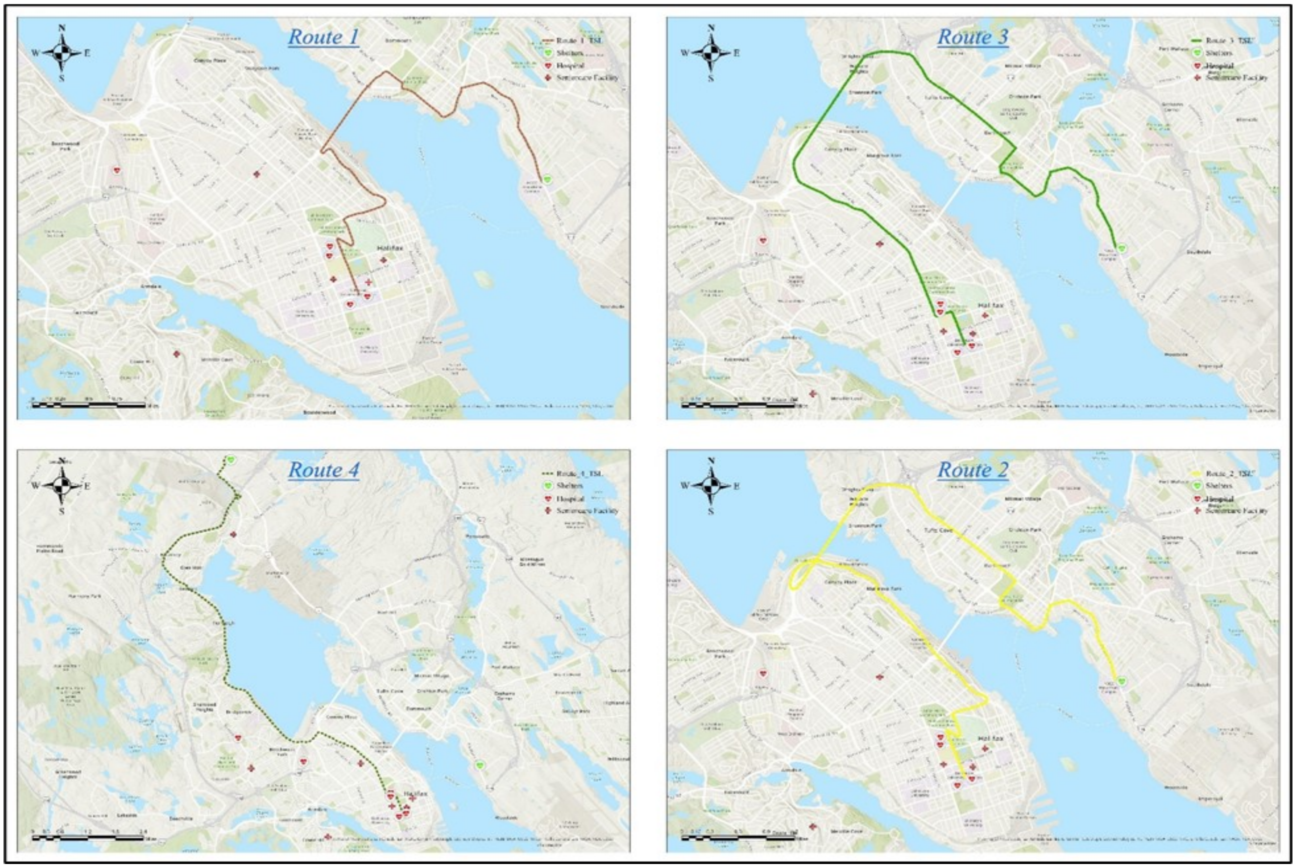

Figure 3-5: Four Designated Evacuation Routes Extended to the Shelter Locations TSL Scenario

Routes 1, 2 and 3 exit the peninsula using two bridges and go to the shelter location Dartmouth General Hospital. Route 4 exits the peninsula by the Bedford highway, taking PMA to the shelter location Cobequid Emergency Centre.

3.4.2 Comprehensive evacuation transport network evaluation

During the analysis of the transport network, a number of network-level results were collected. These outcomes provided valuable insight into the behavior of simulated traffic. The average speed at which regular vehicles and EMVs traveled was a significant indicator of the overall efficiency of traffic flow. The findings made it feasible to determine the average speed of travel across the network, identifying the locations with the most traffic and the stretches of road where drivers could maintain higher speeds. In addition, the total distance traveled by regular vehicles and EMVs provided a measurement of the aggregate vehicle activity on the network. This statistic allowed for an evaluation of total travel demand and levels of congestion, indicating frequently traveled routes or locations with significant travel distances. In addition, EMVs total delay time was an essential indicator of the congested areas on each route and complex intersections on the network. This information is useful for evaluating the network's efficacy in terms of travel time and identifying potential bottlenecks or delays. Overall, these network-level results cast light on the performance of the simulated traffic system, providing the groundwork for further investigation and evaluation of potential network upgrades. Figure 3-6 below illustrates the comparison between the emergency vehicle and regular vehicle speeds throughout the network.

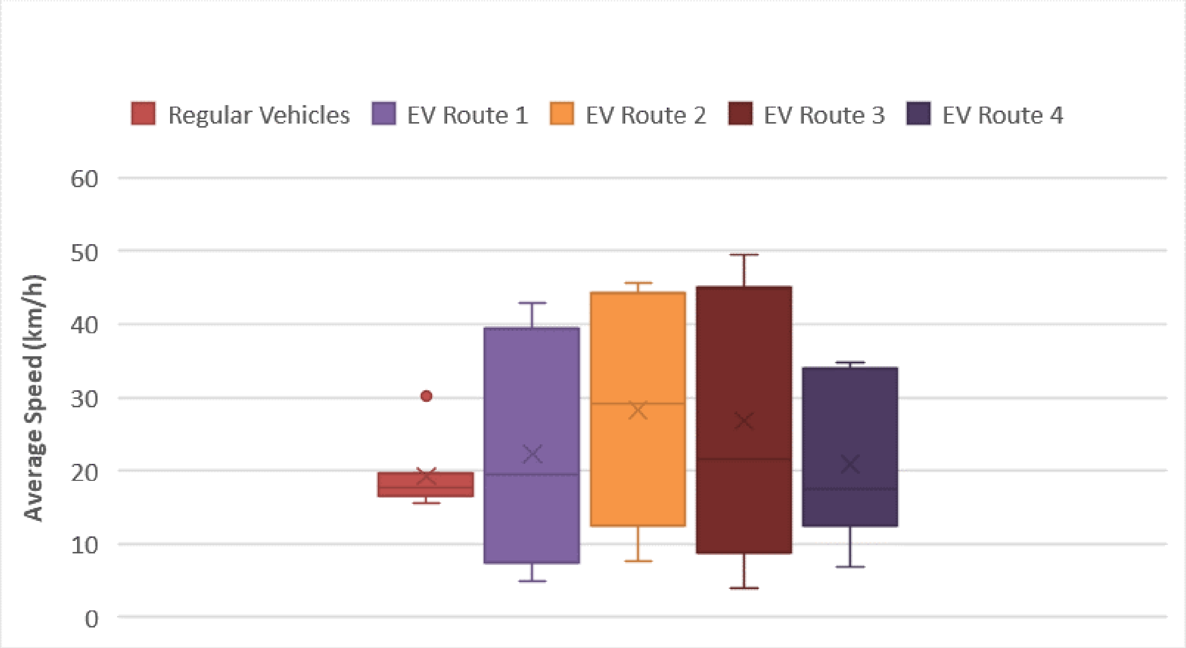

Figure 3-6: Transport Network Average Speed Comparison

As illustrated in Figure 3-6 above, EMVs are operating at a much faster speed on the network as compared to the normal vehicles evacuating. The most important reason for the above said interpretation is that EMVs are following dedicated routes to evacuate the peninsula. While normal vehicles are figuring out the route to evacuate the peninsula. The maximum speed attained by the normal vehicles in the network is 30.23 km/h. While EMVs following Routes 1,2,3 and 4 attain the highest speed of 43 km/h, 45 km/h, 49 km/h and 35 km/h respectively. Concluding that due to the driver's familiarity with dedicated routes, EMVs can travel at much higher speeds compared to normal vehicles, concluding the importance of pre-planned dedicated routes for emergency evacuation operations. Moreover, the lowest speed for the EMVs on certain time intervals of the evacuation gives the idea about the congestion on the dedicated evacuation routes and is a good way to come up with countermeasures to avoid those congested segments in future studies. Next, figure 3-7 below shows the distance traveled by the EMVs in the transport network, with different statistics illustrated for each of the designated evacuation routes in the network.

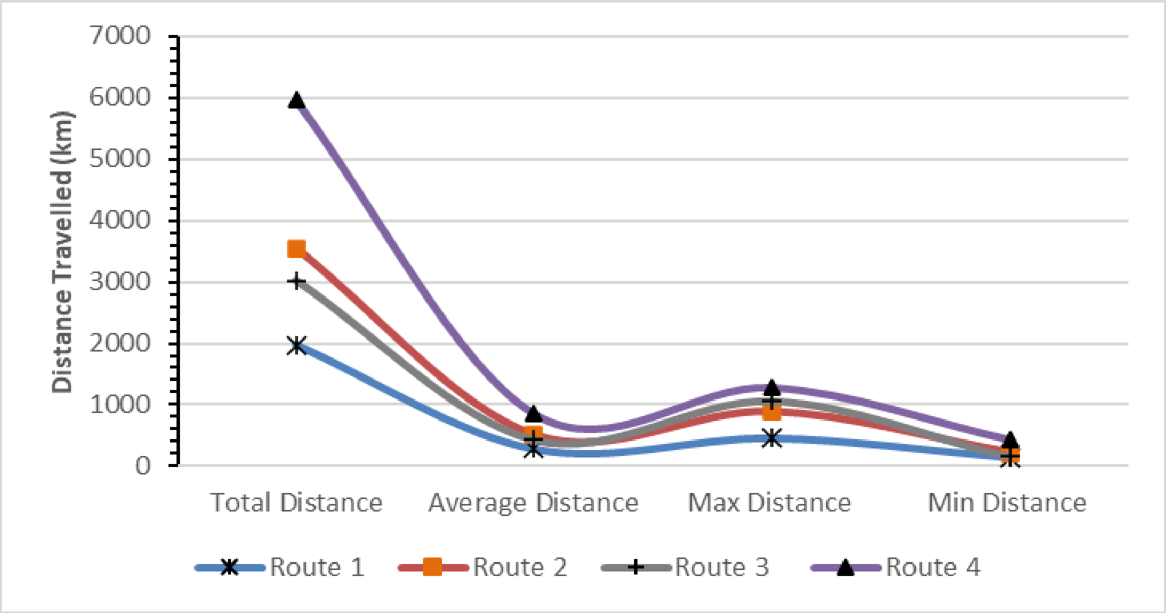

Figure 3-7: Statistics of EMVs Distance Travelled in the Network

As illustrated in the figure 3-7 above, the highest distance traveled by the EMVs is 6000 km on route 4, indicating that route 4 is the longest route of all the routes. The minimum distances traveled by the EMVs on routes 1, 2, 3 and 4 are 144, 221, 153 and 428 km respectively. Concluding the high congestion on the network at those time intervals. Looking at the results of the minimum distance traveled by the EMVs, it can be concluded that EMVs are experiencing significant delays on Routes 1 and 3. EMVs on routes 2 and 4 covered the highest total kilometers, indicating the high total distance of those routes. Finally, EMVs combined total distance traveled for all the designated routes on the network is about 14485 km. Figure 3-8 below shows the average delay experienced by the EMVs for each route in the network and the delay experienced by the regular traffic.

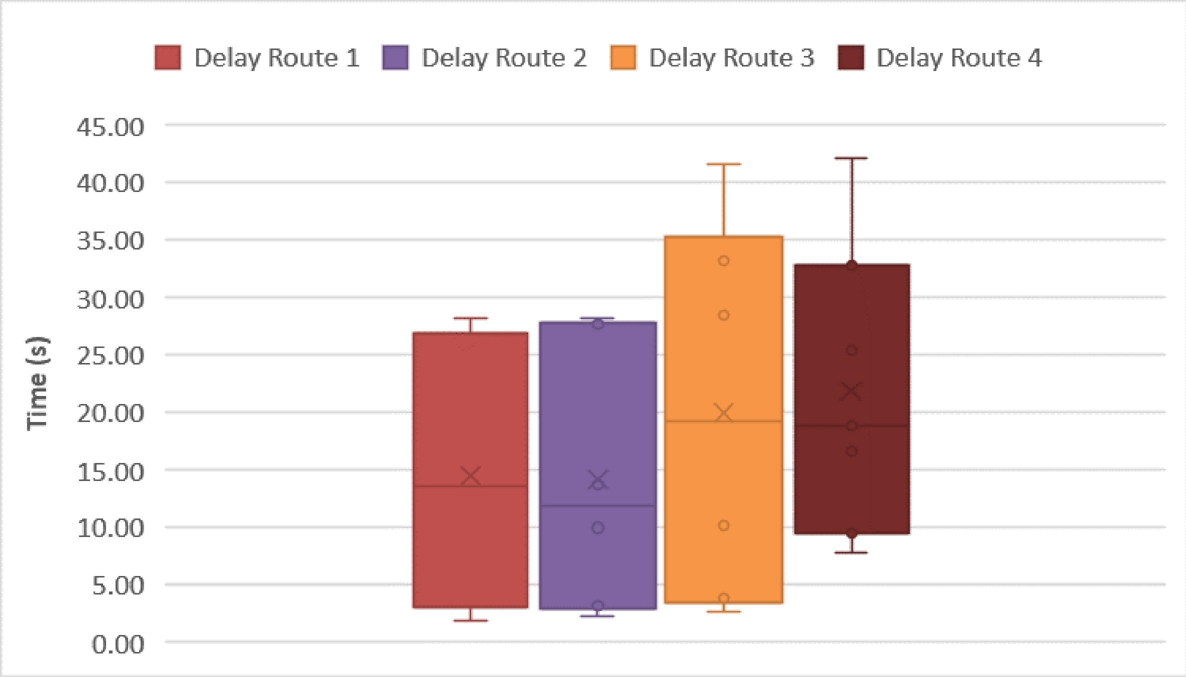

Figure 3-8: Delay Experienced by the EMVs in the Network

As shown in figure 3-8 above, the highest delay experienced by the EMVs is on Routes 3 and 4, 41 and 42 minutes respectively. Concluding the congestion due to the signalized intersection and heavy traffic volume during peak hours on those routes. The average delay time on the network for each route is as follows: 14.5 minutes for route 1, 14.1 minutes for route 2, 20 minutes for route 3 and 22 minutes for route 4. Route 2 with the less average delay time makes that route best for quick and hassle-free emergency evacuation operation of PMA. Route 4 has the highest average delay time, making it the route which takes the highest time to evacuate the peninsula, but is useful as the route has less incident probability and high traffic capacity.

3.4.3 Evacuation Microsimulation Evaluation for AET

This study simulates three PMA evacuation cases to provide a thorough understanding of the functional operation of the EMVs in the network under ODZ and TSL scenarios. The cases traffic evacuation microsimulation model implements are in terms of traffic volume/conditions, and policy direction of a dedicated lane with green signal time for EMVs in the network. Case with a dedicated lane with green signal time provides promising results, with the fastest AET for a single EMV.

3.4.3.1 Case 1: Evacuation Considering AAWT Results

The evacuation microsimulation model implements AAWT in the network for case one to evaluate an EMV's AET to evacuate PMA from the peninsula under ODZ and TSL scenarios. AET is recorded for each of the four routes. Figure 3-9 shows the AET it takes for a single EMV to exit the peninsula through each of the four designated routes under the ODZ and TSL Scenario scenarios.

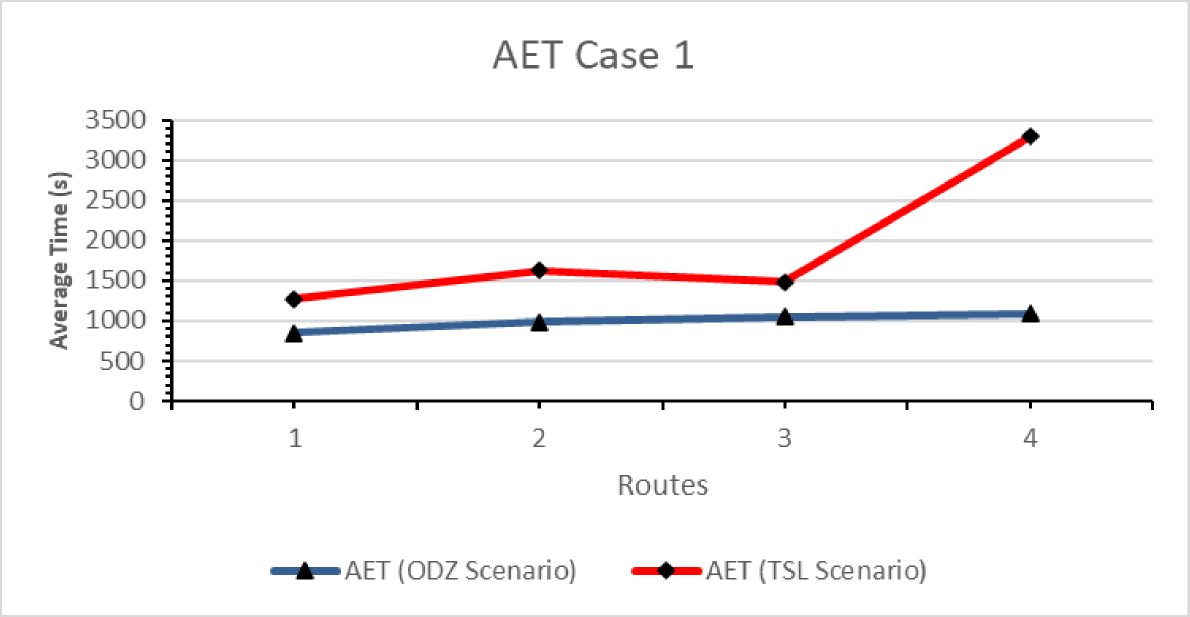

Figure 3-9: AET Considering AAWT Under ODZ and TSL Scenario

As illustrated in figure 3-9 above, for ODZ scenario route 1 is the fastest to evacuate the peninsula taking only 14 minutes. Followed by routes 2, 3 and 4 taking 16.5, 17.5 and 18 minutes to exit the peninsula respectively. Next, the microsimulation model implements AAWT in the network for case one to evacuate PMA from the peninsula under TSL scenario. Figure 3-9 shows the AET it takes for a single EMV to exit the peninsula through each of the four designated routes to transport the PMA to shelter locations. As illustrated in figure 9, for TSL scenario route 1 is the fastest route to evacuate PMA from the peninsula to the shelter location in 21 minutes. Route 3 is the second fastest route taking 25 minutes, followed by route 2 taking 27 minutes. Route 4 takes 55 minutes to transport PMA to the shelter location, longest time out of all four routes.

3.4.3.2 Case 2: Instantaneous Mass Evacuation Results

The second case considers the maximum network traffic volume to simulate the EMVs to evacuate the peninsula through designated four routes. The AET to exit the peninsula for an EMV for this scenario is shown in figure 3-10, for each of the four routes under ODZ and TSL scenarios.

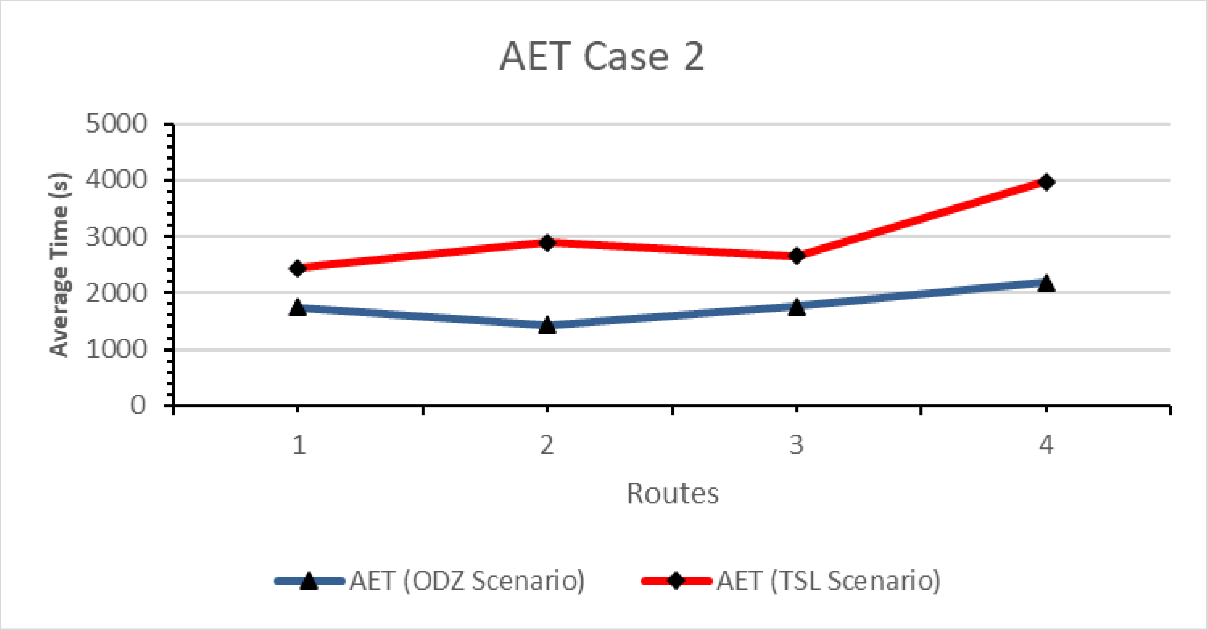

Figure 3-10: AET Considering Instantaneous Mass Evacuation Traffic Volume Under ODZ and TSL scenario

As illustrated in figure 10, under ODZ scenario route 2 is the fastest to exit the peninsula taking 23.8 minutes. Followed by routes 1, 3 and 4 taking 29, 29.3 and 36.5 minutes to exit the peninsula respectively. Considering TSL scenario, the traffic microsimulation model implements maximum network traffic volume to simulate EMVs to evacuate PMA from the peninsula to the shelter locations. Figure 3-10 shows the AET for an EMV to transport PMA to shelter locations. As illustrated in figure 10 above, route 1 is the fastest to evacuate PMA from the peninsula to the shelter location, taking only 40 minutes. Followed by routes 3, 2 and 4 taking 44, 48 and 66 minutes respectively.

3.4.3.3 Case 3: Policy Direction for EMVs Results

This case simulates the EMVs under a policy direction of dedicated lane with green signal time for all the EMVs evacuating PMA. The AET to exit the peninsula for an EMV for this case under ODZ and TSL scenario is illustrated in figure 3-11.

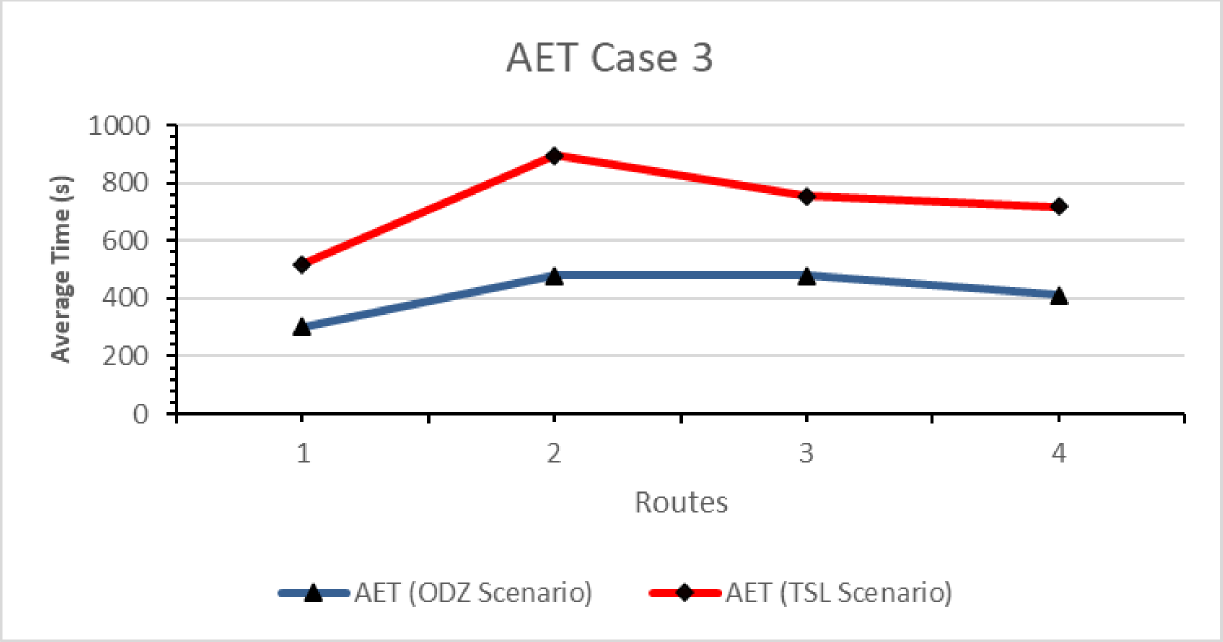

Figure 3-11: Average Evacuation Time for a Policy Direction Case Under ODZ and TSL Scenario

As illustrated in figure 3-11, for ODZ scenario route 1 is the fastest to exit the peninsula taking only 5 minutes. Followed by route 4 taking 6.85 minutes, and routes 3 and 2 take about 8 minutes to exit the peninsula under ODZ scenario. Considering TSL scenario, the model simulates EMVs under a policy direction of dedicated lane and green signal time for all the EMVs evacuating PMA to shelter locations. Figure 3-11 shows the AET to evacuate PMA safely from the peninsula to the shelter locations under TSL scenario. As illustrated in figure 11, the fastest route to evacuate PMA from the peninsula to the shelter location is route 1 taking about 9 minutes. Route 4 is the second fastest route taking 12 minutes, followed by routes 3 and 2 taking 14 and 15 minutes respectively.

3.4.4 Overall AET Comparative Analysis

This study investigates the potential effects of emergency evacuation operations on AET for a single EMV under various network conditions, and two distinct destination-based scenarios which are ODZ and TSL. Traffic evacuation microsimulation model implements three cases to evaluate AET on each of the four designated routes. Figure 3-12 demonstrates the comparison of AET under ODZ and TSL for each case.

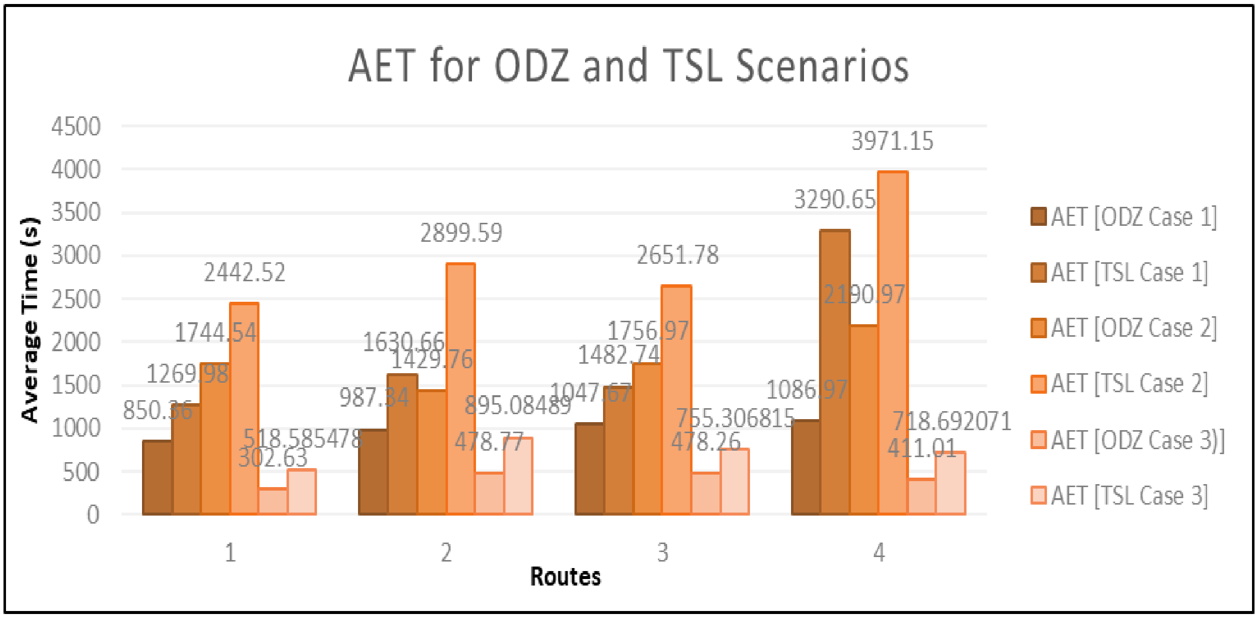

Figure 3-12: AET for All Scenarios

ODZ scenario refers to evacuating PMA out of the peninsula, to get an idea of how long it takes to get PMA out of danger zone. TSL scenario refers to evacuating PMA from the peninsula and dropping them off to selected shelter locations safely. The first case refers to the AAWT volume is used on the network to evaluate the AET. The second case refers to the instantaneous mass evacuation traffic volume used on the network. While third case refers to the policy direction of dedicated lane with green signal time for the EMVs evacuating PMA on the network. As illustrated in figure 12, fastest route to evacuate the peninsula for both scenarios are route 1 and 4 under case 3, taking only 5 and 6.85 minutes respectively for ODZ scenario, 9 and 12 minutes for respectively for TSL scenario. The highest AET to exit the peninsula is under case 2, which is the most realistic case for disaster evacuation. Under case 2 ODZ scenario route 2 is the fastest route to evacuate, as it takes about 23.8 minutes for an EMV to exit the peninsula. For case 2 TSL scenario route 1 is the fastest route to evacuate the peninsula, with AET of 40 minutes for an EMV. Concluding that the destination choice affects the average evacuation time. Next, route 3 can be categorized as the second fastest route for case 2 under both scenarios, taking 29 minutes for ODZ and 44 minutes for TSL scenario to exit the peninsula. The slowest route to evacuate the peninsula for both scenarios is route 4, taking 36.5 minutes for ODZ, and 66 minutes for TSL scenario. For case 1 the fastest routes are the same as case 2, route 2 for ODZ scenario and route 1 for TSL scenario, taking 16.5 and 21 minutes respectively. The slowest route to evacuate the peninsula for case 1 is route 4 for both scenarios, taking 18 minutes for ODZ and 55 minutes for TSL scenario. Concluding that the traffic volume on the road network of Halifax Peninsula doesn't affect the route choice for evacuation in terms of the lowest AET. The overall evaluation of the emergency evacuation operations under mentioned cases, is that the fastest way to evacuate the peninsula is under the policy direction case, and the most realistic way to evacuate the peninsula is under case 2, using routes 2 and 1.

Furthermore, stop delay on routes 2 and 3 for Case 2 is 22 and 13 minutes respectively. Next, the stop delay on routes 2 and 3 for case 1 is 2 and 2.5 minutes respectively. Concluding that the longer stop delay time on route 2 for case 2 results in longer AET. Moreover, for case 1 stop delay is similar for both the routes, and does not affect the AET. Halifax's roads are notoriously narrow and most entry and exit points from the peninsula have bottlenecks. The major cause of high stop delay time for case 2 route 2 is the congestion on Berrington Street before exiting to MacDonald Bridge. The average queue length formed on that segment of route 2 is about 321 meters. furthermore, stop delay on route 3 for case 2 is less than route 2. The reason for the stop delay on route 3 is the traffic congestion on Robie Street during peak traffic volume. The average queue length on the first traffic signal of the Robie Street where EMVs are merging into Robie Street coming from the Veterans Memorial Ln is about 1272 meters. Comparing stop delay and queue lengths formed on mentioned segments, route 2 has less average queue length and more stop delay time. The reason is that some of the signalized intersections on route 2 are also contributing to the stop delay. Concluding that not only queue lengths formed due to congestion on the route, but other factors such as signalized intersections and merging points also contribute to the overall stop delay time. The highest stop delay for cases 1 and 2 are noticed on route 4, about 23 and 31 minutes respectively. The major causes of the delay are the congestion on the first traffic signal of Robie Street, and the congestion at the start of the Bedford Highway, another exit point of the Halifax Peninsula. A queue length of about 735 meters is formed at the start of the Bedford highway exiting the peninsula, the second longest queue length among the three exit points for all evacuation routes. Finally, the stop delay on route 1 for cases 1 and 2 is 2 and 25 minutes respectively. Considering route 1 has the longest stop delay time compared to routes 1 and 2 for case 2, it is the fastest evacuation route for the TSL scenario under case 2. Due to the reason that route 1 is the closest to the shelter location, having the lowest total distance. This concludes that the route's total distance from the shelter location can affect the total evacuation time.

3.5 Conclusion

This study develops a novel approach to test and evaluates four designated evacuation routes for emergency evacuation of persons needing mobility assistance under different network conditions. The four designated routes are incorporated into a microsimulation model for traffic evacuation. The traffic evacuation microsimulation model executes three distinct traffic volume/conditions related cases under two destination-based scenarios. The first scenario analyses the AET to evacuate PMA out of the danger zone, which is just evacuating PMA out of the Peninsula. The second scenario analyses AET to evacuate PMA from Halifax Peninsula and safely transport them to the shelter locations. Considering two scenarios, the AET for a single EMV to evacuate the peninsula is determined for three traffic volume/conditions related cases.

Based on the simulation network level results, the study examined the average speeds of different scenarios within the network. The average speed for regular traffic was determined to be 30.23 km/h. When considering EMVs, it was found that Route 3 exhibited the highest average speed of 49 km/h, followed by Route 2 with an average speed of 45 km/h, Route 1 with 43 km/h, and Route 4 with 35 km/h. These results indicate variations in the average speeds of EMVs across different routes, suggesting potential disparities in road conditions, traffic congestion, or other influential factors. Such findings contribute to a better understanding of the efficiency and effectiveness of emergency vehicle movements in the network, aiding in the development of strategies for optimizing emergency response during critical situations. In terms of the EMV's total distance traveled on different routes, the study observed varying distances for each route within the network. Route 4 recorded the highest distance traveled by an emergency vehicle, reaching 6000 km. On the other hand, the minimum distances traveled by EMVs were 144 km for Route 1, 221 km for Route 2, 153 km for Route 3, and 428 km for Route 4. These disparities in distances highlight the impact of congestion within the network during the specified time intervals. Furthermore, the combined total distance traveled by EMVs across all designated routes on the network amounted to approximately 14485 km. These findings emphasize the substantial distances covered by EMVs to ensure effective response and evacuation during critical situations. The analysis of network-level average delay experienced by EMVs on the designated routes revealed variations in the delay times. Routes 3 and 4 recorded the highest delay times, with 42 minutes each. On the other hand, Route 1 exhibited an average delay of 14.5 minutes, Route 2 had an average delay of 14.1 minutes, Route 3 had an average delay of 20 minutes, and Route 4 had an average delay of 22 minutes. These findings highlight the variations in the delay experienced by EMVs across different routes within the network. Understanding and addressing these delay factors are crucial for optimizing the response time and efficiency of emergency operations.

The AET results reveal that the fastest way to exit the peninsula for both scenarios is by taking routes 1 and 4 under case 3, taking only 5 and 6.85 minutes respectively for the ODZ scenario, and 9 and 12 minutes respectively for the TSL scenario. Keeping in mind that the policy direction case can result in high congestion on surrounding routes. The most realistic way to evacuate the peninsula is under case 2. Under case 2 ODZ scenario route 2 is the fastest route to evacuate, as it takes about 23.8 minutes for an EMV to exit the peninsula. For case 2 TSL scenario route 1 is the fastest route to evacuate the peninsula, with an AET of 40 minutes for an EMV. Case 1 is not the usual road network condition during disaster evacuation, but it can be useful to analyze pre-evacuation measures. For case 1 the fastest routes are route 2 for ODZ scenario and route 1 for TSL scenario, taking 16.5 and 21 minutes respectively. The slowest route to evacuate the peninsula for case 1 is route 4 for both scenarios, taking 18 minutes for ODZ and 55 minutes for TSL scenario. The procedure established in this research can be used in other geographic locations. The route selection model can be used to generate optimal evacuation routes for any geographic location, and the traffic evacuation simulation model can be used to determine the time it takes to evacuate, or any other factors evacuation managers are interested in during evacuation planning.

This research compares the outcomes of ODZ and TSL situations. The significance of both scenarios for evacuation managers is as follows: the ODZ scenario will provide a time estimate for evacuating PMA from the immediate danger zone. While the TSL scenario provides an accurate estimate of the total evacuation time required to transfer PMA to shelter areas. While planning pre-disaster or disaster evacuations for PMA in any geographical location, emergency evacuation managers will find it useful to consider some of the traffic operation and planning criteria derived from the comparison study. The first factor which affects AET for an EMV is the destination choice. When planning disaster evacuation, emergency evacuation managers have to carefully select destination shelter locations to minimize the AET, considering all other parameters related to the safe evacuation of PMA. The second factor is traffic volume, evacuation managers have to consider the traffic volume of the particular evacuation route when planning the evacuation. For this study, the Halifax peninsula was chosen as the study area, and the comparative analysis indicated that the traffic volume does not affect the route choice for evacuation in terms of overall AET. Nevertheless, for other geographic locations traffic volume might affect the route choice for evacuation of PMA. Finally, stop delay time for a particular route and its causing factors are important to analyze when planning evacuation for PMA. Comparative analysis in this study indicated some of the major stop delay causes on the planned evacuation routes such as, congestion, signalized intersections, and merging points on the route. Comparative analysis performed in this study concluded some of the important parameters related to traffic operations, which will help emergency evacuation managers to carefully plan the emergency evacuations for PMA.

The study has some limitations. For example, case 1, though important to consider for emergency evacuation pre-planning, is less likely to be achieved during the disaster evacuation condition in reality, as during a disaster most people are trying to evacuate the city and traffic volumes are high on the network, creating congestion and other traffic disruptions on the network. Further, implementing policy direction of the dedicated lane and green signal time during a disaster evacuation condition can be a challenge for authorities, and can result in high congestion on surrounding routes. Further research is needed to determine the practicality of Case 3 before it can be considered by emergency evacuation managers. This can be done by implementing Case 3 and analyzing its effects on the surrounding routes.

Nevertheless, in the urgent need for emergency evacuation route planning specifically for PMA, this study fills a gap by developing modeling framework to optimally utilize designated emergency evacuation routes, considering different AET under different network conditions to evacuate PMA. As a result of this study, emergency evacuation experts will have a better understanding of the risks and challenges associated with PMA evacuation, and will be better equipped to create policies to mitigate them. This research will help emergency evacuation managers to make protocols to achieve timely planning of evacuation of PMA, understand total evacuation time to prepare for disaster evacuation of PMA, and understand network conditions of where high-level delays and congestions can be expected.

Chapter 4

Conclusion

4.1 Research Summary

Due to natural disasters, people and businesses endure catastrophic losses on a global scale. Emergency evacuations must be well-planned to ensure the protection of evacuees and the resilience of the transportation infrastructure. Transportation planning for vulnerable populations is often limited, and when it comes to evacuation planning, the limitations become even more apparent. Vulnerable populations, such as persons with disabilities, older adults, and those needing mobility assistance, face unique challenges in accessing transportation options that cater to their specific needs during emergencies. The existing transportation infrastructure and services are often not adequately equipped to accommodate their requirements, resulting in limited accessibility and availability of suitable transportation during evacuations. Furthermore, evacuation planning specifically tailored to the needs of vulnerable populations is often lacking, leaving them at greater risk during emergency situations. These limitations highlight the critical importance of addressing transportation and evacuation planning gaps to ensure the safety and well-being of vulnerable individuals during mass evacuations.

While acknowledging the importance of fundamental human factors, such as alleviating the mental burden on evacuees, the predominant emphasis in current research on emergency evacuation planning lies in engineering objectives, including the reduction of evacuation time, optimization of traffic operations, and analysis of evacuation behavior. However, route planning to evacuate PMA safely from the evacuation origin has been ignored. Future evacuation preparations may not be as effective as required due to these constraints. As a result of climate change, it is anticipated that natural disasters and the resultant need for evacuation will occur more frequently, heightening the importance of practical evacuation route planning that takes PMA into account. The primary goal of this study was to look into the traffic and road condition related criteria affecting the evacuation process of PMA from the Halifax Peninsula region of the Halifax Regional Municipality in Nova Scotia, Canada. This study uses MCA to develop a unique route selection model for determining the optimal emergency evacuation routes for PMA, taking traffic and road condition related criteria into consideration. In addition, the research optimizes the objective and subjective weights assigned to criteria, resulting in an optimal set of weights for ranking the optimal route for PMA emergency evacuation. A collision hotspot analysis of the Halifax peninsula is factored into the preliminary screening of emergency evacuation routes. Based on the collision probability, six routes were selected for the optimal route selection analysis. Several methodologies are employed in the study to assign weights to traffic and road condition related criteria. First, objective weight calculations were performed to assign objective weights to criteria based on the information entropy. Following this, operational transportation planners and emergency evacuation managers assigned subjective weights to criteria. After integrating objective and subjective weights during the cloud optimization procedure, an optimal set of criterion weights is obtained. The results reveal that route 2 is the best route for the emergency evacuation of PMA, and the route selection model gives the following three best routes for emergency evacuation of PMA, from the Halifax Peninsula: $R_2 > R_3 > R_4 > R_1$.

This study develops a novel methodology for testing and evaluating four designated evacuation routes for emergency evacuation of PMA under varying network conditions. The four designated routes are incorporated in a microsimulation model of traffic evacuation. The traffic evacuation microsimulation model executes three unique traffic volume/conditions-related cases based on two destination-based scenarios. The first scenario examines the AET to evacuate PMA from the danger zone, which refers to evacuating PMA just outside of the peninsula. The second scenario examines the AET to evacuate PMA from the Halifax Peninsula and transport them safely to their designated shelters. Two destination based scenarios and three traffic volume/conditions-related cases are used to calculate the AET for a single emergency vehicle to evacuate the peninsula. The results show that taking routes 1 and 4 under Case 3 is the quickest way to exit the peninsula for both scenarios, requiring only 5 and 6.85 minutes respectively for the ODZ scenario, and 9 and 12 minutes respectively for the TSL scenario. Case 2 represents the most practical condition for evacuating the peninsula. For case 2 ODZ scenario, route 2 is the quickest way to exit the peninsula, taking just over 23 minutes. For case 2 TSL scenario route 1 is the fastest route to evacuate the peninsula, with an AET of 40 minutes for an emergency vehicle. Case 1 is not a typical road network condition during disaster evacuation, but it is beneficial for analyzing pre-evacuation procedures. For case 1 the fastest routes are route 2 for ODZ scenario and route 1 for the TSL scenario, taking 16.5 and 21 minutes respectively. The slowest route to evacuate the peninsula for case 1 is route 4 for both scenarios, taking 18 minutes for ODZ and 55 minutes for the TSL scenario.

4.2 Research Contributions

This project contributes to a growing literature to support emergency evacuation transportation of vulnerable population. The novel contribution of this research is the creation of a model for selecting emergency evacuation routes for people who require mobility assistance, which accounts for eight different traffic volume and road condition-related criteria impacting emergency evacuation operations for people who require mobility assistance. The route selection model uses the cloud model to combine the objective and subjective weights assigned to criteria, resulting in an optimal set of criteria weights. In addition to employing the traffic evacuation microsimulation model to evaluate and assess the average evacuation time, the study's distinguishing feature is that it uses the optimal evacuation routes found by the route selection model as designated evacuation routes. The most significant contributions of this study include the following improvements to emergency evacuation for individuals requiring mobility assistance.

1. The study develops a route selection model through a hybrid MCA process using the entropy weight method, cloud model optimization, and the TOPSIS method to determine the optimal evacuation routes for individuals requiring mobility assistance in the event of an emergency. To reduce the incident probability of evacuation routes, the model uses collision hotspot analysis to identify evacuation routes for initial route assessment.

2. The route selection model takes eight traffic and road condition-related parameters into account as the key influencing factors when selecting emergency evacuation routes.

The parameters used are based on actual emergency evacuation operations and the opinions of transportation planners.

3. Furthermore, the route selection model developed utilizing hybrid MCA approach weights criteria in the following manner. First, it uses information entropy to calculate the objective weights of criteria. Following that, it uses a cloud model optimization process to optimize and combine objective and subjective weights provided by emergency evacuation managers. Using this technique, the optimal collection of criterion weights is developed.

4. This study develops a microsimulation modelling framework for evacuation of PMA. The study identifies optimal evacuation routes as designated evacuation routes from the route selection model for incorporation into the traffic evacuation microsimulation model. The average emergency evacuation time of a single emergency vehicle is then evaluated based on two destination-based scenarios and three traffic volume/condition-related cases.

5. This study concludes with a comparison of AET results for destination scenarios to determine the fastest evacuation routes to evacuate PMA in a secure manner, as well as a discussion of the significant traffic operations/planning factors influencing AET and route selection to evacuate PMA.

4.3 Concluding Remarks and Future Research Directions

Using Multi-Criteria analysis, this study develops a novel method for selecting the best emergency evacuation routes for PMA, taking into account traffic and road condition-related criteria. In addition, the study optimizes the objective and subjective weights assigned to criteria and generates an optimized set of weights for ranking the optimal route for PMA emergency evacuation. Initial screening of emergency evacuation routes is performed with a collision hotspot analysis of the Halifax peninsula in consideration. For the optimal route selection analysis, six routes were chosen based on the probability of collisions. Multiple mechanisms are used to assign weights to traffic and road condition-related factors. Initial objective weight calculations were performed to designate objective weights to criteria based on the information entropy. Following that, practicing transportation planners and emergency evacuation managers assigned subjective weights to each criterion. Combining objective and subjective weights, the cloud optimization procedure produced an optimized set of criterion weights. This study develops an innovative method for testing and evaluating four designated evacuation routes for the emergency evacuation of PMA under different network conditions. Incorporating the four designated evacuation routes into a microsimulation model. Within two destination-based scenarios, the traffic evacuation microsimulation model executes three distinct traffic volume/conditions cases. The first scenario analyzes the AET to evacuate the PMA from the danger zone, which requires moving the population off of the Peninsula. The second scenario examines the use of AET to evacuate PMA from Halifax Peninsula and transport them to shelters in a safe manner. Considering two scenarios, the AET for evacuating the peninsula with a single emergency vehicle is determined for three traffic volume/conditions-related scenarios.

The procedures developed in this research can be used in other locations and the route selection optimization model can be updated to include newly discovered variables for PMA's emergency evacuation route selection. The route selection model can be used to generate optimal evacuation routes for any geographic location, and the traffic evacuation simulation model can be used to determine the time it takes to evacuate, or any other factors evacuation managers are interested in during evacuation planning. Because the majority of PMA residents will require assistance, this analysis accounts for emergency vehicles that will be used to evacuate the town. However, other vehicles may be required in emergency situations, so further study can be done to investigate the use of generic vehicles. In addition, the initial screening procedure for emergency evacuation routes only considers collision hotspot analysis to select the initial routes with the lowest incident probability. However, the impact of the catastrophe itself can render some neighborhoods' traffic routes inaccessible due to flooding or excessive fire. Future studies can consider disaster impacts when conducting preliminary evacuation route screening. In addition, the authors propose enhancing the route selection model by incorporating PMA destination choice and capacity constraints. One of the limitations of the study is its reliance on historical collision data. Due to the a lack of observed collision data pertinent to the evacuation procedure during natural disasters, the study had to rely on historical records to analyse collision patterns.

However, this approach may not adequately reflect the unique dynamics and obstacles that exist in a real-world evacuation scenario. Future research would benefit immensely from incorporating real-time collision observations during disasters to address this issue. By collecting and analysing collision data unique to evacuation situations, researchers can develop more accurate models and strategies to enhance the safety and effectiveness of evacuation procedures. Moreover, it can be difficult for authorities to implement policy directives for the dedicated lane and green signal time during a disaster evacuation, resulting in heavy congestion on adjacent routes. Before emergency evacuation managers may consider Case 3, further research into its viability is required. This can be achieved by executing Case 3 and analyzing its effects on the surrounding routes. Finally, in future studies, performing sensitivity analysis for each criterion or selected criteria would be a valuable approach to understanding the impact of weight variations on the final route ranking. By systematically adjusting the weights of individual criteria, researchers can assess how these changes influence the overall outcome, and more importantly, the ranking of evacuation routes. This sensitivity analysis would enable a comprehensive evaluation of the robustness and stability of the route selection model, providing insights into the potential variations in route rankings due to changes in criteria weights. Understanding the degree of change in route rankings as weights are modified can contribute to the optimization and refinement of the evacuation planning process, ensuring the selection of the most effective and efficient routes for the safe evacuation of vulnerable population.

Nevertheless, in the urgent need for emergency evacuation route planning specifically for PMA, this study fills a gap by developing an emergency evacuation route selection model for PMA considering traffic and road condition related criteria. Also, by developing a modeling framework to optimally utilize designated emergency evacuation routes, considering different AET under different network conditions to evacuate PMA. The findings of this research will enable emergency evacuation management experts in formulating policies and managing challenges and dangers linked with PMA evacuation by providing knowledge on how to mitigate them. The model can be used to plan pre-disaster evacuation of PMA using normal weekday traffic volume conditions, or it can be used to plan evacuation during the disaster using maximum traffic volume conditions. As a result of this study, emergency evacuation experts will have a better understanding of the risks and challenges associated with PMA evacuation, and will be better equipped to create policies to mitigate them. This research will help emergency evacuation managers to make protocols to achieve timely planning of evacuation of PMA, understand total evacuation time to prepare for disaster evacuation of PMA, and understand network conditions of where high-level delays and congestions can be expected.

The authors of this study have outlined three valuable takeaway lessons as follows:

- This research provides a comprehensive framework for emergency evacuation route planning that specifically caters to the needs of vulnerable populations, such as Persons Needing Mobility Assistance (PMA). By considering multiple criteria and factors unique to these populations, the study identifies and evaluates dedicated evacuation routes to ensure their safety and well-being during mass evacuations.
- The integration of microsimulation modeling in the evaluation process allows for thorough testing of designated evacuation routes under different scenarios, offering valuable insights into their effectiveness and efficiency. Policymakers and emergency management agencies can make informed decisions based on these findings, leading to the development of proactive evacuation strategies to address the growing risks of disasters, such as wildfires in Nova Scotia and around Canada.
- By prioritizing the transportation needs of vulnerable populations and incorporating them into emergency response plans, this research contributes to creating a more inclusive and equitable approach to emergency management. The study's evidence-based recommendations enhance the overall resilience of communities, ensuring that vulnerable individuals are well-supported and protected during crisis situations, ultimately saving lives and minimizing the impact of disasters on these populations.

In conclusion, this thesis has made significant contributions to the field of emergency evacuation route planning for vulnerable populations. By considering various criteria and factors specific to the needs of vulnerable individuals, this research has developed a comprehensive framework for identifying and evaluating dedicated evacuation routes. Through the utilization of microsimulation modeling, the designated evacuation routes have been thoroughly tested and evaluated under different scenarios. The findings of this study provide valuable insights into the effectiveness and efficiency of these routes, enabling policymakers and emergency management agencies to make informed decisions and develop proactive evacuation strategies. For example, the integration of multiple criteria in the route planning process ensures that the transportation needs of vulnerable populations are adequately addressed, promoting their safety and well-being during mass evacuations. The outcomes of this research have proven to be particularly valuable in addressing the growing risks of wildfires in Nova Scotia and their impact on vulnerable populations, such as PMA. The recent evacuation of 16,000 individuals, including those in nearby senior care centers, highlights the urgency and importance of developing operational plans specifically tailored to the needs of these vulnerable groups in the face of wildfire threats and other similar disasters. This research serves as a crucial resource for policymakers, offering evidence-based recommendations for improving emergency response plans and enhancing the overall resilience of communities when faced with crisis situations. By prioritizing the needs of vulnerable populations and incorporating them into evacuation route planning, this thesis contributes to creating a more inclusive and equitable approach to emergency management, ultimately saving lives and minimizing the impact of disasters on vulnerable individuals.

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